THE SEPARATION OF WORK AND RESIDENCE:

A Case Study of Employees of Fort Garry Industrial Area No. 1, Winnipeg

by

Richard J. Powell

A thesis submitted to the Faculty of Graduate Studies at the University of Manitoba in partial fulfillment of the requirements for the degree of Master of City Planning.

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PREFACE

The journey to work is a fundamental aspect of human ecology. It has profound impacts on:

1) the image and structure of urbanized areas through the requirement for and location of arterial roadways and public transit rights of way which in turn affect adjacent land use;

2) the quality of life in the urban environment through the noise and air pollution generated by commuters;

3) the increasing rate of consumption of limited fossil fuel resources;

4) the expenditure of public funds for transit systems, transportation corridor improvements and maintenance;

5) the expenditure of private funds for transit fares or owning and operating private automobiles;

6) the loss of time spent on commuting which could have been devoted to other, more enjoyable or productive persuits.

In order to minimize and rationally plan for commuting, it is necessary to understand the many factors affecting the length of the worktrip or the travel time separation between homes and jobs. This thesis attempts to further that end, and it is divided into three principle areas:

1) An analysis of the factors affecting the separation of work and residence;

2) A discussion of the development of mathematical spatial interaction models which may be used to predict the separation between work and residence; and,

3) A case study of the work-residence separation of employees of an industrial area in Winnipeg.

The work outlined above could not have been completed without the support and assistance of many individuals. I would like to acknowledge my indebtedness to:

1) The Transportation Development Agency of the Canadian Government for their financial support in the form of a TDA Fellowship;

2) The managers of the firms in Fort Garry Industrial Area No. 1 who gave of their time and provided the majority of the data required for the case study;

3) The Streets and Transportation Division of the City of Winnipeg who provided 1971 travel time data;

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5) To my wife, Sheila, for her continuing patience and assistance.

CHAPTER I

FACTORS AFFECTING THE SEPARATION OF WORK AND RESIDENCE

Introduction

For any given place of work, there is an unique frequency distribution of its employees residing at various time-distance intervals away. This work-residence separation distribution is the product of two basic factors; the distribution of the supply of suitable residential opportunities around the workplace, and the demand distribution of employee work trip travel propensities.

The residential opportunity distribution is uniquely determined by the surrounding land development pattern and transportation system. Generally, opportunities increase as the area of development around the work trip destination increases, and then they fall off as the limit of urban development is reached.

At the metropolitan level, the opportunity distribution is affected by several parameters of urban structure. For example, average opportunity spacing increases with city size, spread and land use uniformity, and it decreases with increasing population density, compactness and intermingling of land uses. A city's transportation infrastructure also affects the nature of the opportunity distribution, especially when it is measured in terms of travel time, through the directness and speed of the commuting modes and routes it provides.

The opportunity distribution will be different for each commuter, or each relatively homogenous group of commuters with a common destination or origin, according to individual definitions and perceptions of what is a suitable opportunity, as well as the relevant characteristics of the residences and workplaces which are available. For example, what is a suitable employment opportunity will vary according to the jobseeker's occupation, experience and salary expectation. Similarly, a suitable residential opportunity will be determined by the individual's income, socio-economic status, family size, life cycle stage, tenure preference, taste for dwelling type, neighbourhood services and amenities. Opportunities may also be restricted for some individuals by virtue of racial discrimination or some form of subsidization.

The second major factor involved, the distribution of work trip travel propensities, measures the willingness and ability of commuters to expend time, money and effort in travelling to work. As a result of travel impedance, most people prefer to travel as little as possible, while a few are willing and able to travel further. Work trip travel propensity is largely dependent on psychological or subjective factors such as attitudes toward work and home, and enjoyment of travel. These factors vary considerably throughout the population and are difficult to quantify. Since work trip travel involves money costs, ability to pay or income is to a large extent a quantifiable determinant of ability to travel. Similarly, factors such as occupation, sex, education and life cycle stage which are correlated with income may be indicative of travel propensity.

Mathematical models of work-residence separation or work trip interaction normally include only the two basic factors as independent variables; that is, trip ends or trip end opportunities and travel time or, in some cases, intervening opportunities, as an inverse measure of travel propensity. The remaining factors are accounted for by adjustment variables, the estimation of empirical parameters, or the disaggregation of the model for specific geographic zones or population groups.

The objective of this chapter is to gain further insight into the variables affecting work-residence separation and the manner in which they interact. As such, it serves partially as a basis for Chapter II, which discusses the theoretical basis for several analytical spatial interaction models and the role of the variables and parameters used in developing them to reliably predict commuting patterns. It also serves as a basis for identifying those factors which indicate promising directions for effective planning policies aimed at reducing average commuting times, thereby conserving energy, time and money for individuals and society at large.

Travel Impedance and Work-Residence Separation

The spatial separation of an individual's place of work and his residence is, within the limitations imposed by the distribution of such places, a consequence of a pair of complex personal decisions. It is a fundamental postulate of this thesis, and a great deal of other research, that a decision as to one's place of residence is linked to a previous decision as to place of employment--or vice versa--and is based, partially at least, on a desire to reduce or limit the spatial and temporal separation between the two locations. In the words of J. Douglas Carroll, Jr.,

> ...while many factors are involved in the selection of homes and places of work, the persistence of the desire to minimize the distance separating workplace from home acting through each individual worker may be the single element which can create pattern out of the aggregate choices of large numbers of workers. It is, of course, obvious that these choices are differentially limited for each individual worker so that only in large aggregates can patterns begin to appear.[1]

The pattern which is consistently observable is that employees of a specific workplace diminish as a proportion of resident population with increasing distance from that place of work. In other words, workers are not indifferent to the length of their work trip in the selection of their residence. This is not to say that workers as individuals or as a group select their homes and jobs in such a way that the journey to work is minimized; however, they do as a group tend more toward minimization than indifference.[2]

One of the most fundamental factors affecting the separation of work and residence is the quality of separation itself, which tends towards

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1 J. Douglas Carroll, Jr., "Home-Work Relationships of Industrial Employees," (Ph. D. dissertation, Harvard University, 1950), p. 21, quoted in Leo F. Schnore, "The Separation of Home and Work: A Problem for Human Ecology," Social Forces 32 (December 1954): 337.

2 John R. Hamburg et al, "Linear Programming Test of Journey-to-Work Minimization," Highway Research Record 102 (1965): 67-75.

minimization. There is inherent in traversing physical distance a cost, an effort, a disutility, which is usually termed travel impedance. To the individual this may have many components; including, time lost to other activities, out-of-pocket cost, and physical effort or discomfort. All of these tend to inhibit travel and presumably result in a limitation of the total time spent travelling by each individual. Since "nearly half of all trips from home are made to work," [1] it is not unreasonable to expect that this desire to limit travel would find common expression in an attempt to reduce the separation between an individual's home and his place of work.

The actual separation between work and residence may be measured in a number of ways. The length of the worktrip itself is probably the best gauge of effective separation; although, on some occasions, the straight line distance between home and work is used as a proxy. Trip length is usually expressed in terms of over-the-road distance or trip time. In order to account for speed variation, congestion effects, and in some cases, terminal delays, time is generally the preferred measure.

In terms of the traveller's immediate perception, trip time and out-of-pocket costs are undoubtedly the most important measurable deterrents to travel. While some attempts have been made to combine time and costs

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1 John F. Kain, "The Journey-to-Work as a Determinent of Residential Location," <u>Papers and Proceedings of the Regional Science Association</u> 9 (1962): 139.

into a single travel impedance measure, it has proven very difficult to place a uniform and meaningful dollar value on time. For this reason, for a given mode of travel one often assumes that out-of-pocket costs, and sometimes terminal delays, are either approximately equal for all travellers or are of secondary importance to them in comaprison with actual travelling time. Travel time, then, is widely accepted as the most convenient and meaningful measure of effective work-residence separation.

The variation in average travel time for various groups of workers or work-trip situations can, therefore, be used to draw conclusions about the many worker and urban characteristics which influence home-job separation. Alan M. Voorhees and Associates used data from a number of cities in the United States and Canada to analyse the factors affecting the length of urban worktrips.[1] They found that the average worktrip length in most cities was between ten and fifteen minutes for automobile drivers. They also synthesized a representative auto-driver worktrip travel time distribution for an average North American City. This distribution, presented in figure 1, can be shown to approximate a gamma distribution.[2]

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1 Alan M. Voorhees and Associates, Factors and Trends in Trip Lengths, National Cooperative Highway Research Program, Report No. 48 (Washington: Highway Research Board, 1968); and Alan M. Voorhees and Associates, Factors, Trends and Guide-lines Related to Trip Length, National Cooperative Highway Research Program Report No. 89 (Washington: Highway Research Board, 1970).

2 The gamma density function takes the form: $f(t)=K\left\{t^{(\bar{t}-\delta_t^2)/\delta_t^2}\right\}\left\{e^{-(\bar{t}/\delta_t^2)t}\right\}$
where $f(t)$ = the relative frequency of trips of duration t
K = a constant
e = the base of the natural logarithm (2.71828)
$\bar{t}$ = average trip duration
δ_t = the standard deviation of trip duration.

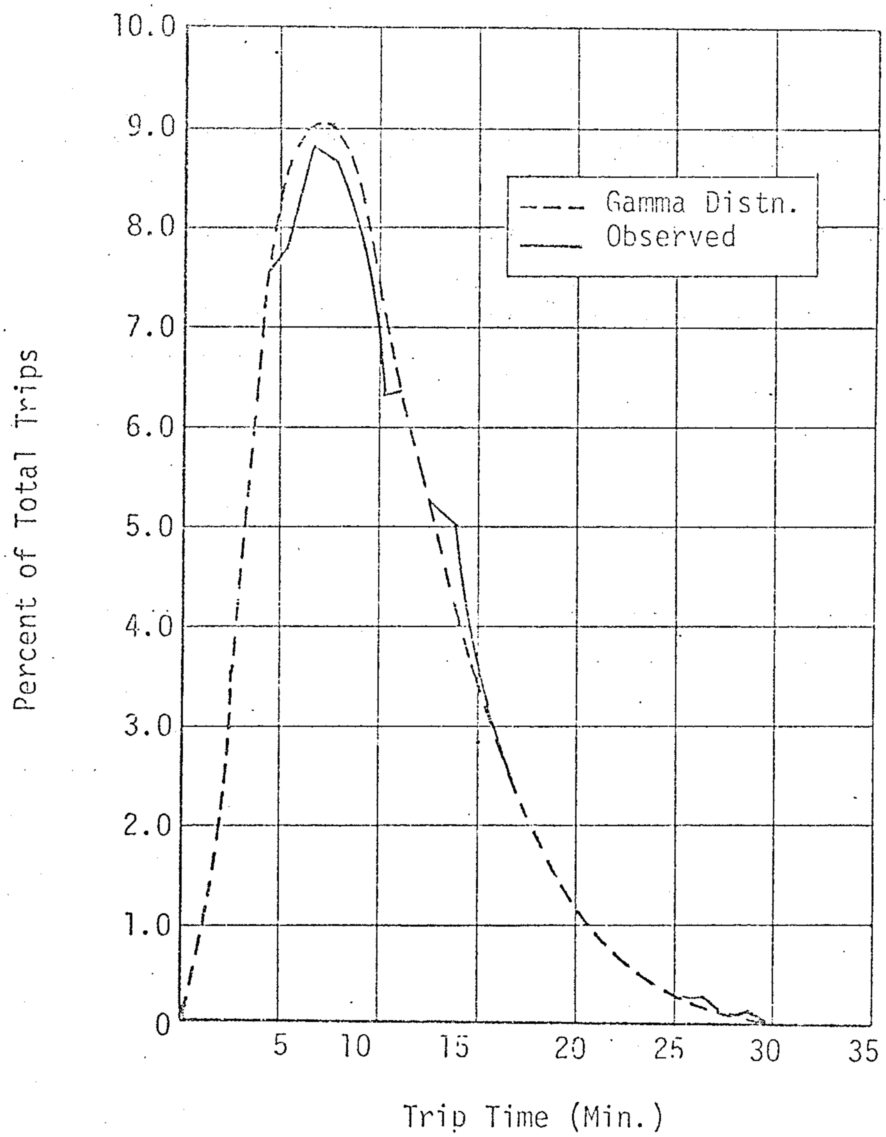

FIGURE 1: Auto-Driver Work Trip Distribution, Erie, Pa.

(Source: Voorhees and Associates, "Factors and Trends", Appendix B)

At first glance, the distribution appears to contradict the notion that there is a desire on the part of workers to reduce home-work separation, since there are very few of the shortest worktrips. The reason, of course, is that normally there are few residences in the immediate proximity of places of work. One of the most important factors affecting the separation of home and work is the distribution of residential opportunities with respect to workplaces, or vice versa.

The Work-Residence Opportunity Distribution

Historical land development patterns, traditional zoning practices, economies of scale and proximity, and many other factors have over the years produced urban landscapes composed of residential districts distinct from employment districts. Many North American cities have a central core devoted almost exclusively to commercial and office use, which is surrounded by residential development except for a few sectors dedicated to industrial use. Even where there are residences in proximity to jobs, very often the types and prices of the residences are not suited to the requirements of employees working nearby. As a result, we have downtown office workers commuting to new housing in the suburbs while industrial workers from inner-city neighbourhoods commute to suburban industrial parks.

The development pattern described above significantly limits the opportunity for a worker to find a suitable residence close to his job. It is not surprising, then, that many concerned with urban transportation problems have advocated altering current development practice to place appropriate housing in close proximity to employment centres.[1] Edward M. Bergman has even suggested that a performance standard for residential zoning be the radius of a reasonable commuting distance from an employment centre.[2] In other words, if a proposed residential development of a certain type and affordability were located more than a given distance from a centre employing sufficient potential consumers of such housing, the necessary zoning would not be granted.

The impact of the current distribution of homes and jobs on the length of worktrips is a factor which must be given careful consideration in analysing any apparent desire to reduce work-residence separation.

Voorhees and Associates have also defined a worktrip length opportunity distribution, which is based upon the frequency distribution of the travel time separation between all potential homes and jobs in various North American Cities.[3] This distribution, shown in figure 2, appears to be approximately normal in form and is largely a function of city structure and transportation network speed.

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1 See for example, Wilfred Owen, The Accessible City (Washington: The Brookings Institute, 1972) and Hans Blumenfeld, Canadian Planning Issues (Ottawa: Canadian Institute of Planners, 1976) p. 11.

2 Edward M. Bergman, Eliminating Exclusionary Zoning: Reconciling Workplace and Residence in Suburban Areas (Cambridge, Mass.: Ballinger Publishing Company, 1974), pp. 37-39.

3 Alan M. Voorhees et al, "Factors in Work Trip Lengths," Highway Research Record 141 (1965): 27.

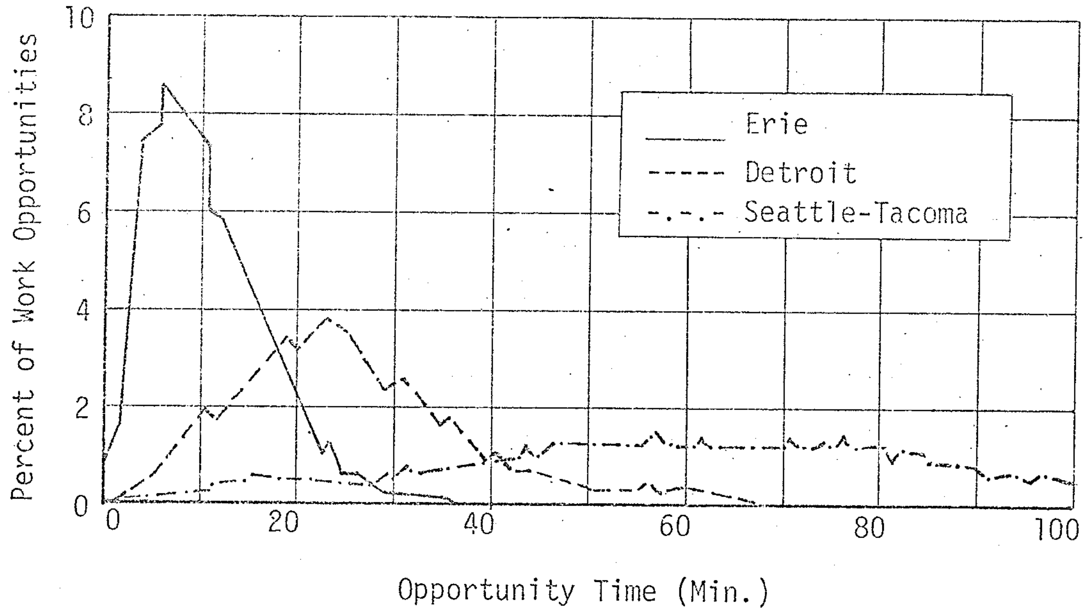

FIGURE 2: Work Trip Opportunity Distribution for Three Cities

(Source: Voorhees et al, "Factors in Work Trip Lengths," p.28)

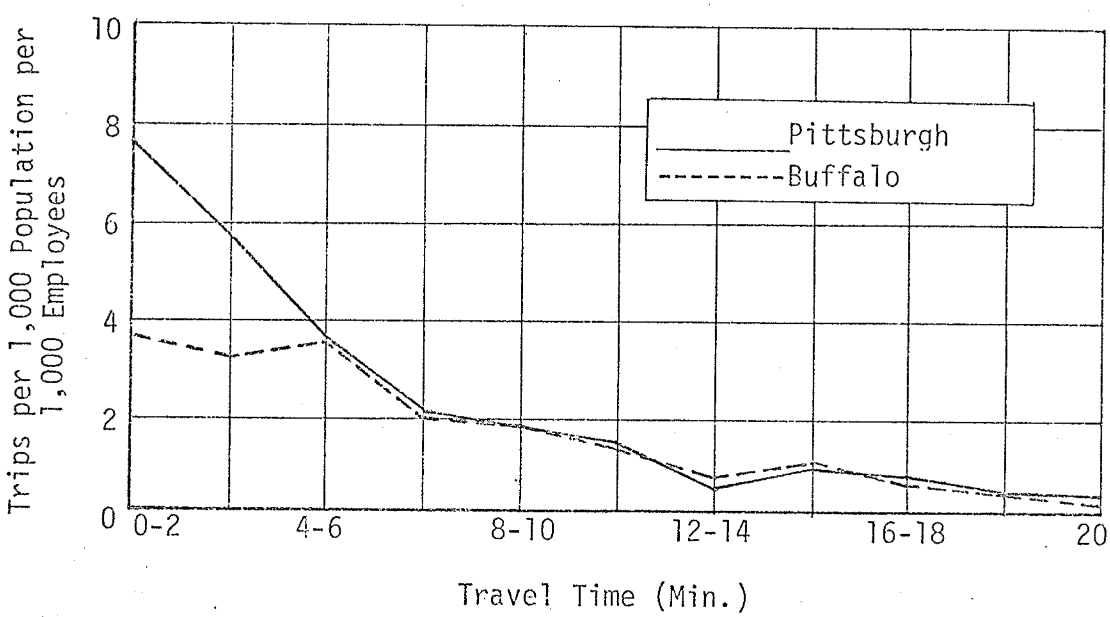

FIGURE 3: Auto Driver Work Trip Rates by Travel Time, Normalized by Plant Employment. (Source: Keefer, Airports, Shopping Centers and Industrial Plants, p.82)

When the trip length opportunity distribution, or the population distribution[1] around a particular concentration of employment, is taken into account, it has been found that the shortest feasible worktrip lengths do predominate. For instance, Louis J. Keefer found that auto driver trips per one thousand population, normalized by plant employment, for worktrips to industrial plants in Pittsburgh and Buffalo were distributed as indicated in figure 3.[2] Generally, the frequency of trips appears to exhibit an exponential decline with increasing trip length.[3]

The necessity of considering an opportunity distribution for worktrip origins can also be brought into perspective by examining two basic interpretations of the apparent tendency to limit work-residence separation. As we shall see in Chapter II, the difference between these two interpretations are manifest in the two fundamental spatial interaction or trip distribution models, currently in use. In that emphasized by

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1 Population distribution may be used as a rough proxy for residential distribution.

2 Louis E. Keefer, Urban Travel Patterns for Airports, Shopping Centers and Industrial Plants National Cooperative Highway Research Program, Report No. 24 (Washington: Highway Research Board, 1966) p. 82.

3 The exponential distribution is given by $f(t) = \lambda e^{-\lambda t}$ where $f(t)$ is the frequency of worktrips of duration t, e is the base of the natural logarithm and λ is an empirically determined parameter. It serves as a convenient generalized mathematical representation of travel propensity phenomena as suggested by its analytical tractibility and the usual shape of observed data. It provides a widely applicable, statistically generated family of curves which allows the user to select an optimal parameter value to suit the case at hand, rather than estimating a separate model for each application.

the Gravity Model, the separation between two points is assumed to possess an inherent impedance where each additional unit of distance, time, or cost serves to incrementally reduce the porbability of a trip interchange.

Another assumption, embodied in the Opportunity Model, is that impedance will prompt an individual to travel only as far as necessary and no further. Under these circumstances, the amount of competition for suitable opportunities closer at hand will determine the ultimate distance at which satisfaction may be achieved. It is difficult to ascertain which approach best represents the actual perception and motivation of trip makers, and undoubtedly, elements of both are involved.

Impedance and the distribution of suitable trip-end opportunities are the most fundamental factors affecting the separation of work and residence; however, there are other, more empirical, factors which moderate the basic relationships already described. These other factors include observable characteristics of the urban structure, transportation system, place of work, place of residence, and worker population involved.

Urban Structure

Mean worktrip length appears to be directly proportional to the size of urban centre concerned. Voorhees found that cities in the 100,000 population range had average automobile worktrip lengths in the order of ten minutes, while cities of approximately 1,000,000 had trip lengths in the order of fifteen minutes.[1] And J. Douglas Carroll concluded that average work-trip length would be minimized for cities of about 10,000 people where there was sufficient, diverse industry.[2]

Reasons for a positive correlation between population size and increasing worktrip length are not difficult to postulate. Larger centres have a greater number and wider distribution of residential and work opportunities increasing the average opportunity, or potential, length for worktrips. This, combined with better transportation facilities, greater specialization of residential areas, and concentration of industry, increases the probability of longer trips to work. In larger centres there is a fluid labour market and a greater proportion of workers, new to the job, who probably have not adjusted their work-residence separation to a personal optimum. On the other hand, in smaller centres, available residential and employment opportunities are usually situated in closer proximity and the labour market is generally more stable.

The density and spread of urban centres also affect average worktrip length. Trip lengths are typically shorter in compact, high density cities such as New Orleans and longer in low density, scattered development of the type found in Fort Worth.[3] Voorhees and Associates

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1 Voorhees et al, "Factors in Work Trip Length", p. 26.

2 J. Douglas Carroll, Jr., "Some Aspects of the Home-Work Relationships of Industrial Workers", Land Economics 25 (1949): 420.

3 Voorhees et al, "Factors in Work Trip Length", p. 26.

suggest that average worktrip distance is almost a linear function of the average distance workers reside from the Central Business District. In other words, mean trip length is a function of the radius of gyration of a city's population. They also conclude that in a city growing by an extension of population and employment at the periphery, worktrip length is directly proportional to population. In a city growing by infilling vacant land at roughly the same density as the surrounding built up area, the average trip length will not change significantly. While, in a city which grows by increasing existing densities, the average trip length will decrease.[1]

The relative concentration of employment and housing also affect trip length. Those cities with heavy concentrations of employment in the center generally have longer average worktrips than cities of similar size and density where employment is more evenly distributed. One might conclude that the trend toward suburban industrial parks, particularly if they are not too large, will have a positive effect on reducing worktrip length. There is already some evidence that industrial decentralization has reduced trip length for suburban commuters relative to inner-city residents. Voorhees and Associates report,

> The findings that were made for Detroit on a sub-area basis indicate that dynamic changes are occuring over time in the length of the worktrip. In 1953, the center city residents had the lowest worktrip length and the highest housing cost. In the suburbs trip lengths were higher but housing costs were lower. In 1965 the pattern with respect to transportation costs was completely reversed. People in the centre city had higher trip lengths whereas those in the suburbs had lower trip lengths.[2]

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1 Voorhees et al, "Factors in Work Trip Length" p. 36.

2 Voorhees and Associates, "Factors, Trends and Guidelines, p. 4.

Unfortunately, the workers who suffer lengthened journeys to work as a result of industrial relocation to the suburbs are those least able to afford it. In a 1974 survey of employees of relocated plants in Toronto, it was found that trip times generally increased for those earning less than $9,000 per year while they decreased for high-income groups.[1] This resulted in a significant level of dissatisfaction and job change in the lower-income groups. It suggests the need for a more uniform distribution of low-cost housing as well as employment. It may also be desirable to retain considerable employment for workers with lower education and skill levels in the inner-city area.

The Transportation System

The travel mode employed in the worktrip and the quality of the transportation infrastructure in a city appears to have considerable impact on the spatial separation between home and work but relatively little on the temporal separation.

Both Carroll and Leo G. Reeder found that the average distance travelled in a particular mode increased with the range and speed characteristic of it.[2] For example, those walking generally travel less than one or two miles to work; those using public transit usually travel one to

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1 City of Toronto Planning Board, "Industrial Relocation and Its Impact on Employees", Assumption Study No. 1 on the Future of Industry in the City of Toronto, June 1975, p. 35.

2 Carroll, "Aspects of Home-Work Relationships", p. 417; and Leo G. Reeder, "Social Differentials in Mode of Travel, Time and Cost in the Journey to Work", American Sociological Review 21 (February 1956): 59.

five miles, and those using private autos often travel in excess of five miles. However, the distribution of time spent travelling appears to remain about the same for all modes; with the possible exception of public transit, which may take much longer when waiting time and the frequency of stops are considered.

It is interesting to note that time spent travelling to work has remained relatively stable over the years. Indications from Charles Dickens' literature dealing with London are that people walked to work in about twenty minutes, which is about the average time spent now in getting to work by automobile in a comparably sized city of about two to three million people.[1]

Private automobile is generally the fastest, most comfortable and convenient mode and it is also the most expensive. In recent surveys by Statistics Canada, seventy-five percent of all commuters rode in a private automobile.[2] It appears that the unsurpassed popularity of the private automobile for the journey to work is due in large part to the added mobility it offers. Some even suggest that the lengthened journey to work permitted by the automobile supplements or supersedes migration where the motive is to seek new employment opportunities.[3]

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1 Alan M. Voorhees and Salvatore J. Bellomo, "Urban Travel and City Structure", Highway Research Record 332 (1970): 131.

2 Chris Hanlon, "Results of a National 'Travel to Work' Survey", Canadian Institute of Planners Forum (January 1977) p.8

3 Katé K. Liepman, The Journey to Work (New York: Oxford University Press, 1944), pp. 10-19; and, Amos H. Hawley, Human Ecology (New York: The Ronald Press, 1950) p. 337.

With respect to access to individual modes, car ownership is the most significant factor affecting choice of mode for the worktrip. Proximity to transit service is generally important only to captive transit patrons who do not have access to a private automobile. In Canada, about fifteen percent of commuters use public transit; whereas, the majority have access to it for the worktrip.[1]

The quality of a city's transportation infrastructure also affects the average distance between jobs and homes. Usually better public transit systems and roadway networks result in greater average worktrip distances.

For instance, Los Angeles' extensive freeway system gives it larger trip miles and shorter trip minutes than cities of comparable size. Voorhees and Associates found that worktrip distance increases noticeably as peak hour[2] network speed increases while worktrip travel time decreases only slightly.[3]

It would seem that potential time savings in the journey to work are being traded for increased spatial mobility. This does not necessarily contradict the postulate that people attempt to reduce or limit work-residence separation. It simply implies that temporal separation is more the limiting factor; whereas, increased spatial separation may be

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1 Hanlon, "National Survey", p. 8.

2 It should be clear that work-trip lengths are most sensitive to the operation of the transportation system during the period when most of the work trips are made, the congested peak hour.

3 Voorhees, Factors and Trends, p. 23.

tolerated in return for a better job or residence. Such findings do, however, refute the notion that urban traffic congestion can be reduced by transportation system improvements alone and suggest that planning complementary residential and employment opportunities in close proximity may be a more fruitful approach.

The directional distribution of workers' homes around an employment center reflects the directional quality of the urban transportation system. Employees tend to live in greater numbers and further away on those sides on which travel to work is the easiest. As Keefer notes,

> Workers are reluctant to cross major travel barriers -- namely the wide river valleys, spanned irregularly by traffic crowded bridges. Most live on the same side of the valley as the plant, out of proportion to the distribution of the population.[1]

Similarly, there is usually a disproportionately greater number of work-trips originating from the suburban side of a plant than the CBD side.[2] This is undoubtedly an attempt on the part of plant employees to avoid delays associated with crossing through the downtown area with its numerous stoplights and considerable peak hour congestion. It could also be the result of high-speed expressways, which cater to access in the suburbs but deny it in central-city areas because of the limited land available for interchanges there and the operational priority awarded to through traffic.

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1 Keefer, Airports, Shopping Centers and Industrial Plants, p. 78.

2 This is less likely if the plant is located further out into the suburbs, since there would be some advantage to an inner-city resident able to travel to work in the direction opposite the major peak-hour flow.

There is in most urban areas a built-in bias in the transportation system in favour of radial travel versus peripheral travel. The exception is in areas where ring roads or beltways have been constructed. A radial bias is particularly evident in most public transit systems where the majority of routes are downtown oriented and peripheral travel requires several transfers.

Place of Work Characteristics

The stability of the workplace and the type of industry involved can have considerable impact upon work-residence separation.

Several researchers have pointed out the fact that older industrial plants have a much more compact distribution of employee residences about them than do recently-established or rapidly-expanding plants.[1] New firms or newly relocated firms tend to draw workers from farther afield at first. As time passes and convenient residential opportunities become available, permanent employees are likely to move closer to overcome the cost and inconvenience of a long journey to work.

Those firms which are economically-stable and employ predominantly older, permanent, full-time, single shift employees tend to have a closer distribution of employee residences than those firms, which are less economically stable or employ large numbers of new, seasonal, temporary,

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1 Leipman, The Journey to Work, p. 15; Carroll, "Aspects of Home-Work Relationships", p. 418; and Schnore, "Separation of Home and Work", p. 338.

part-time, or shift workers. It seems that increased job security and commitment result in a reduction in commuting distance. In a study of industrial installations in Flint, Michigan, Schnore found that evening and night shift workers actually increased in numbers with increasing distance from their place of work.[1] Shift employees are often periodically hired, marginal workers with little seniority and perhaps relatively little commitment to their jobs. It is also possible that their unique distribution is due to a second job, possibly part-time agriculture, or because of the ease with which they can travel to work during off-peak hours.

It has been reported that employee work-residence separation varies with the type of industry involved. Technically specialized firms employ highly skilled, highly paid workers who commute further than the average worker. Beverly Duncan found that employees of firms specializing in electrical machinery, printing and publishing, and chemical and allied products come from greater distances than those employed by firms involved in textiles or fabricated metals.[2] Aside from the possibility of temporary local labour market shortages in specialized trades, the most likely explanation for this phenomenon is that those employees with higher incomes could afford to travel further to exercise their tastes and preferences for residential accomodation.

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1 Schnore, "Separation of Home and Work", p. 339.

2 Beverly Duncan, "Factories in Work Residence Separation: Wage and Salary Workers, Chicago, 1951, "American Sociological Review" 21 (February, 1956): 53.

Separation also varies with type of employment because of the current locational preferences of different employers. Large manufacturing firms have generally relocated to lower cost land in suburban industrial areas to accomodate expansion and the space requirements of modern production line and material handling techniques. Warehousing and distribution firms have in large measure followed them toward the periphery and taken advantage of the cheaper land and less congested suburban transportation terminals. Office employment, meanwhile, has remained heavily concentrated in the central business district, although there is some outward movement associated with the development of commercial subcentres and suburban "office parks". Assuming most blue collar workers still tend to reside in less expensive accomodation in inner city areas while more affluent white collar workers reside primarily in the suburbs, these trends indicate an increase in average worktrip lengths for workers in the manufacturing and distribution sectors relative to office workers.

The size of individual firms apparently has little effect on work-trip length. In a study of Massachusetts manufacturing plans Carroll found that only those firms with 5,000 or more employees showed a significant increase in the average work-residence separation of their employees.1

In a more recent study of industrial plants in the United States, Keefer also found that plant employment had relatively little impact on trip length, although larger plants did have a slightly wider distribution of employee residences.[2] Greater worker awareness of large employers, a

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1 Carroll, "Aspects of Home-Work Relationships, p. 419.

2 Keefer, Airports, Shopping Centers and Industrial Plants, p. 73.

smaller proportion of plant employees which can be accommodated in a limited number of nearby residences, and labour market shortages due to rapid company growth are all possible reasons why large individual firms might draw workers from farther afield than their smaller counterparts.

Of more importance to work-residence separation, however, is large industrial districts or concentrations of industrial plants. As previously indicated, the greater the concentration of employment opportunities, the less likely residences will be situated in proximity to any individual plant, the greater will be competition for nearby residences and the more likely the transportation system will have been designed to facilitate travel from greater distances.

Place of Residence Characteristics

In the long term and at a macro-scale, housing consumers, by virtue of their collective action do exert some influence over the type and location of residential units placed on the market. In the short term, however, the ability of individual households to find suitable residential opportunities in proximity to their places of work is severely constrained by the supply characteristics of the existing local housing market.

A location convenient to work is only one of many considerations of the residential consumer. According to his needs, preferences, and ability to pay, he seeks a varying quantity and quality of residential space. Some of the other housing attributes usually-considered are number of rooms, physical quality of the dwelling unit, lot size, neighbourhood quality, level of public services, taxes, type of tenure and affordability.

Proximity to other centers of activity significant to daily living might also be considered a determinant of residential location, since as Carroll notes, "trips to work are short but shopping, school and church trips are shorter."[1] Michael A. Stegman reports similar findings and also points out that suburban residents usually enjoy greater accessibility to such services than inner city residents.[2] It would appear that as planners and developers have recognized that these facilities are a necessary adjunct of residential living, their resultant distribution is now so widespread that they are acceptably close to the majority of urban residences. Thus, while proximity to schools, parks, shopping facilities, and other amenities might affect location within a neighbourhood, their relative quality as opposed to proximity is more likely to influence location within the urban area as a whole.

The demand for various types of housing is closely related to the socio-economic characteristics of the consuming household. Although, as sociologist-planner Herbert Gans points out, ownership of a suburban single-family dwelling unit is probably still the ideal for most North

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1 Carroll, "Home-Work Relationships", p. 86.

2 Michael A. Stegman, "Accessibility Models and Residential Location", A.I.P. Journal 35 (January, 1969): 28.

Americans,[1] especially during the child-rearing stage of their life cycle, an increasingly smaller percentage of households can afford this low density lifestyle in the face of rapidly rising housing costs. Young adults and older couples whose children have grown up often prefer to live at higher densities for reasons of economy and convenience. Lower income households are usually restricted to renting, and sometimes owning, smaller quantities of urban space. Similarly, household income often determines housing and neighbourhood quality, as well as whether the accommodation selected is new or old. It is generally agreed that affordability of the housing package is one of the key determinants of residential location.

The affordability or cost of a given residential package will depend upon the amount of space consumed, the location rent, and the level of quality and amenity sought. The price a household must pay per unit of residential space will vary from one location to another according to Kain because of location rent which is "an economic rent which landlords can obtain from households for more accessible sites."[2] He assumes the price per unit of residential space of a stated quality and amenity decreases with distance from workplace because of competition to economize on transportation expenditures around significant concentrations of employment. Kain's location rent is based upon an urban land market

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1 Herbert J. Gans, "The White Exodus to Suburbia Steps Up" The New York Times Magazine (January 7, 1968), p. 94, quoted in Stegman, "Accessibility Models", p. 27.

2 Kain, "The Journey-to-Work", p. 139.

theory, which implies that location rents are very high in the center of the city, decline steeply with distance from the core, and level off toward the outer fringes of the metropolitan area. Figure 4 graphically represents the location rent function where Q2 represents a successively greater quantity of residential space than Q1 and so on.

While unit location rents are lowest at the periphery, it is also true, as Stegman suggests, that accommodation at the periphery is generally newer, more functional, and possesses a higher quality of environment and level of amenity.[1] Unit housing values and costs, exclusive of accessibility considerations, probably increase gradually with distance from the core, much as illustrated in Figure 5.

The location rent function is dominant, however, probably not so much because of residential competition as Kain suggests, but rather because of competition for central sites by nonresidential commercial and office uses. The result of the combined phenomena is the fact that residential locators can obtain more desirable land for housing in the outer rings of the city at lower prices than they would pay for less desirable land closer to the central business district. In other words, a consumer's incentive for residing in the suburbs is not only that he can obtain more residential space for his dollar but that he can also obtain better residential space on the average. The interesting aspect of this situation is that lower income households continue to reside near the urban

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1 Stegman, "Accessibility Models" pp. 24-25.

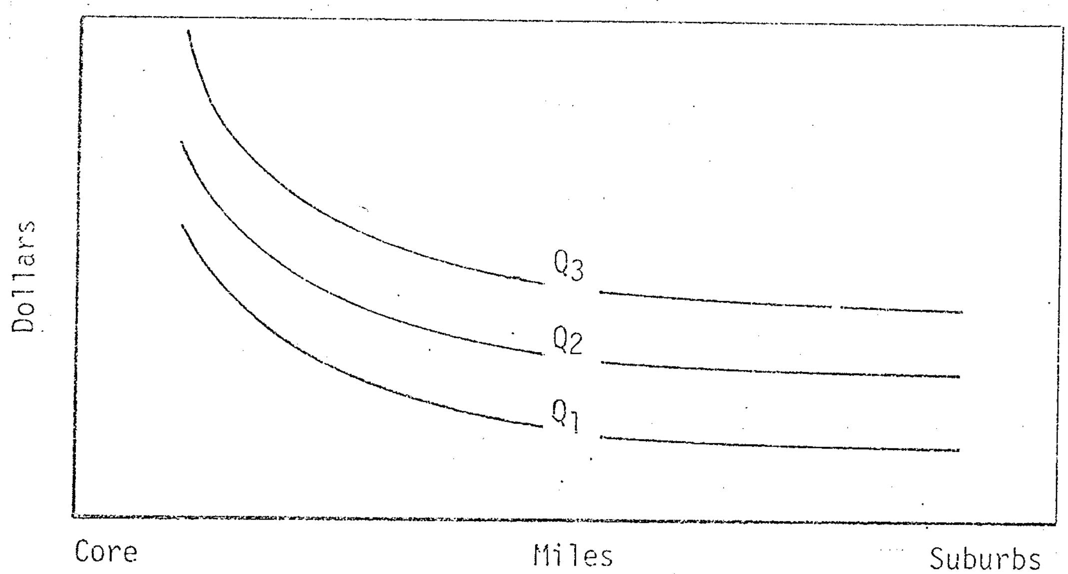

FIGURE 4: A Form of Kain's Location Rent Function

(Source: Kain, "The Journey-to-Work," p.141)

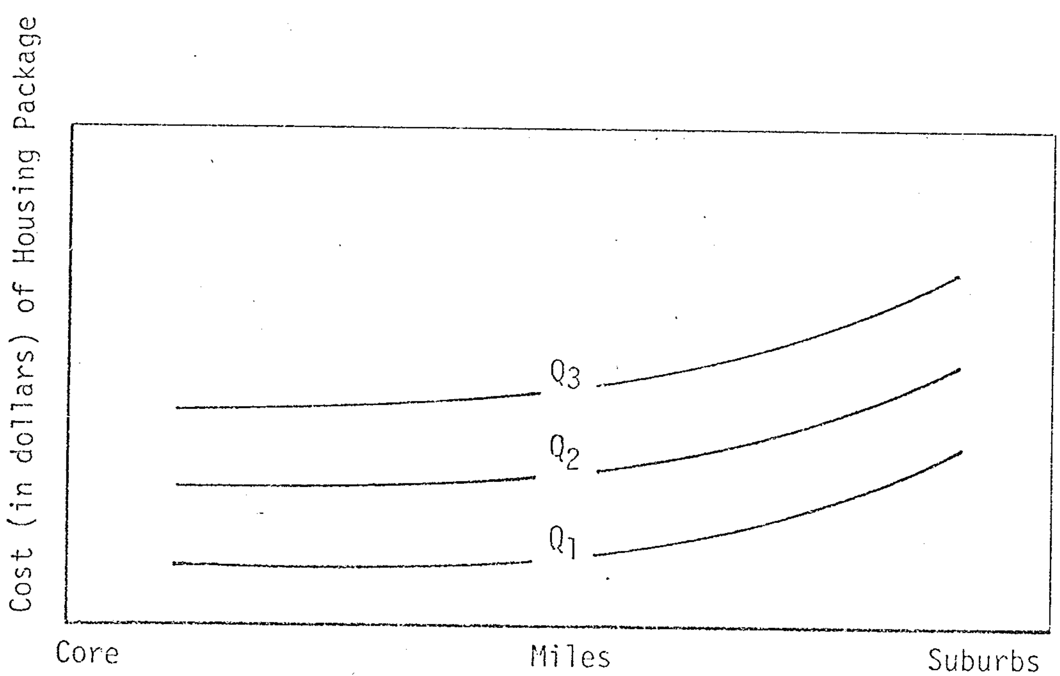

FIGURE 5: An Illustrative Form for a Housing Cost Function

(Source: Stegman , "Accessibility Models, p.23) core and the reason is probably not so much to economize on transportation costs, in view of increasing industrial decentralization, but rather because of the traditional absence of sufficiently small, affordable quantities of residential space in the form of multifamily and rental housing in the suburbs. This pattern is slowly shifting, however, and it is likely that a more homogenous distribution of income groups will result as suburban densities increase.

There exists, at the present time, a debate by residential location theorists over the importance of the accessibility or job proximity factor in determining residential location. The accessibility based economic models of Alanso, Harris, Kain, Lowry and Muth imply that the desire to be close to work is the key factor, which arranges the distribution of worker residences into a rational pattern.[1] They do recognize, however, that residential space is not an inferior good and assume that households will trade off increased journey to work expenditures for decreased unit site expenditures in accordance with their preference for low density living and ability to pay for larger amounts of space.

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1 William Alonso, "A Theory of the Urban Land Market" Papers and Proceedings of the Regional Science Association 6 (1960): 156 and Location and Land Use: Toward a General Theory of Land Rent (Cambridge: Harvard University Press, 1964); Britton Harris, Basic Assumptions for a Simulation of the Urban Residential Land Market (Philadelphia: Institute of Environmental Studies, University of Pennsylvania, 1966); Kain, "The Journey-to-Work"; Ira S. Lowry, "A Model of Metropolis", Memorandum RM-4035-RC (Santa Monica: RAND, 1964), cited in Stegman, "Accessibility Models", p. 29; and Richard F. Muth "The Spatial Structure of the Housing Market" Papers and Proceedings of the Regional Science Association 7 (1961): 207-220.

Another group of researchers, including Butler et al, Cantanese, Goldstein and Mayer, Simmons, and Stegman, challenge the importance of the journey to work in residence choice and the value of workplace based residential models.[1] They would prefer alternative models which explain a household's residence location primarily on the basis of household tastes and preferences, particularly for neighbourhood characteristics, with little regard for place of work. They contend that their empirical evidence shows that the quality of the neighbourhood, in terms of socio-economic status, race, crime, density, home ownership and similar factors, is the most important determinant of residential location. While some of their research does indicate limited association between job change and residence change and a lack of emphasis on reduced commuting as a motive for moving, their work is far from conclusive.[2] Very little has been done to actually determine if workplace is actually further or nearer as a result of a move, irrespective of the stated reasons for the move. In more recent work, Barry M. Moriarty and H. James Brown found

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1 E.W. Butler et al, Moving Behavior and Residential Choice: A National Survey, National Cooperative Highway Research Program, Report No. 81 (Washington: Highway Research Board, 1969); A.J. Cantanese, "Home and Workplace Separation in Four Urban Regions", Journal of the American Institute of Planners 37 (September, 1971): 319-325; S. Goldstein and K. Mayer, "Migration and Journey to Work "Social Forces 42 (May, 1964): 479; J.W. Simmons, "Changing Residence in the City", Geographical Review (October, 1968): 637; and, Stegman, "Accessibility Models".

2 Some evidence to contrary in cases of plant relocation is provided in; Toronto Planning Board "Impact on Employees:", p. 44.

that neighbourhood quality and workplace location were both important elements of the residential location decision, although each emphasizes one factor over the other.[1] Perhaps, though, this is indicative of reconciliation between the two groups and of an understanding that with increasing affluence and mobility, neighbourhood characteristics narrowly circumscribe what is considered to be a suitable residential opportunity, while attraction to workplace still creates an orderly pattern of choice among more limited competing suitable opportunities.

The quantity, as well as quality, of available housing affects home-work separation. With increased vacancies and available units, the opportunities for finding a suitable residence in proximity to work is increased. If the housing market is tight and opportunities are limited, there is a good chance that one's initial choice of residence will not be optimum in terms of place of work location or housing package preferences. This is particularly true in light of the fact that when supply is limited, what housing is available is usually marginal in terms of quality. Later, during a high vacancy period, adjustments may occur either in terms of moving closer to work or perhaps further away, if this is necessary to obtain the desired standard of accommodation.

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1 Barry M. Moriarity, "Socioeconomic Status and Residential Locational Choice" Environment and Behaviour 6 (December, 1974): 448-469; and, H. James Brown, "Change in Workplace and Residential Location," Journal of the American Institute of Planners (January, 1975): 32-39.

It should be noted that the rental market situation will often be different from the home ownership or condominium market. Locational adjustments will usually occur sooner in the rental market because renting households are usually more mobile.

It should also be noted that choice of residence and adjustment is dependent upon the household's limited perception of the market. The consumer has imperfect knowledge and is only aware of those vacancies which he sees advertised or which are brought to his attention by real estate agents. These, of course, represent only a portion of the total vacancies at any given time, and as a result intra-urban migration behaviour is, at best, only intendedly rational.

Household Characteristics

Of the many factors affecting work-residence separation, several of the most important relate to the socio-economic and psychological characteristics of the worktrip-making household.

Average worktrip length has been found to vary in a fairly consistent manner with household income level, and it has been suggested that models attempting to explain the spatial interaction between work and residence be stratified or disaggregated according to income levels.

Duncan, Kain, Fisher and Sosslau, and Voorhees are among those, who found that average work-residence separation increased as household income increased.[1] However, Voorhees suggests "the explanation for this does not seem to lie in the fact that high income groups have a greater propensity for travel, but instead is due to the spatial distribution of residential areas and employment for different income groups." In other words, there has historically been a greater physical separation between homes and jobs associated with higher income groups than between those of lower income groups.

This does not deny the fact that households with higher incomes are more able to trade-off increased journey to work expenditures for lower unit site expenditures, as suggested earlier in this chapter, and as indicated in Alonso's equation:

$$Y = K(t) + q\ P(t) + \sum_i P_i\ Z_i$$

where limited income, Y may be expended on commuting transportation costs, K(t), which are a function of work-trip length, t, or on housing costs for a quantity, q, of housing at unit location rent, P(t), or on all other household expenditures, $\sum_i P_i Z_i$, of price, P_i, and quantity, Z_i.[2] One must conclude that the higher the family income, the more

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1 Duncan, "Factors in Work-Residence Separation", p. 50; Kain "The Journey-to-Work", p. 148; R.J. Fisher and Arther B. Sosslau, "Census Data as a Source for Urban Transportation Planning", Highway Research Record 141 (1966): 52; Voorhees, Factors, and Trends, p. 18.

2 Alonso, Location and Land Use, pp. 19-21.

flexible the location of residence with respect to work. Whether or not this actually results in a longer worktrip depends to some degree on the opportunity distribution of homes and jobs suitable to a given income level.

As has already been suggested, increasing industrial decentralization has lengthened the worktrip of inner city blue collar workers relative to suburban white collar workers. This has been largely because of the increasing standard of living and relative availability of the private automobile, as well as flat fare public transit service. It is probable that the impact of income on trip length has diminished over the last few decades. However, there is a good chance that with impending fossil fuel shortages, more expensive gasoline and wider usage of zone to zone transit fares, ability to pay may reassert its importance as a factor governing worktrip length.

Much of the work associating work-residence separation with income levels also examined occupational differentials.[1] Generally, it was found that average separation increased with occupation status level according to the following hierarchy: professionals, managers, sales workers, clerical workers, craftsmen, operatives, labourers and service workers. The order of these occupations corresponds roughly with the average occupa-

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1 See for example, Duncan "Factors in Work-Residence Separation", p. 50, Kain, "The Journey to Work" p. 148; Fisher and Sosslau, "Census Data", p. 54; James O. Wheeler, "Some Effects of Occupational Status on Work Trips", Journal of Regional Science 9 (April, 1969): 71.

pational income from highest to lowest, with the significant exception that craftsmen and operatives earn more on the average than sales and clerical workers.

The fact that sales and clerical workers tend to reside further from their jobs, than income considerations alone would suggest, is consistent with the notion that separation is largely determined by the distribution of suitable residential opportunities. Several sociological studies indicate that residential areas are stratified or segregated according to socio-economic status.[1] This is the result of a desire on the part of individual home seekers to increase social accessibility to compatible neighbours of equal or higher status and maintain social distance from those they consider to be of a lower status. Usually people prefer to live in neighbourhoods and houses of similar quality as those whom they perceive to share similar values and aspirations and who have similar or socially desirable, educational, family or occupational backgrounds. Thus it is not surprising that white-collar sales and clerical workers tend to live close to white-collar managers and professionals, while craftsmen and operatives live close to other blue-collar workers and exhibit a corresponding worktrip distribution pattern. In Beverly Duncan's words, "it would probably be possible to reproduce approximately the observed pattern of differentials in work-

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1 Several such studies are summarized in Moriarity, "Socio-economic Status".

residence separation with a model which assumes that labour force members will reside in that area nearest their workplace, which is compatible with their socio-economic level."[1]

Many consider occupation to be the single most important factor of the several that enter into a determination of socio-economic status[2] and occupational prestige is often a major factor affecting household location. Given this, it would seem reasonable to disaggregate spatial interaction models relating homes and jobs according to occupation as an alternative to income.

Journey to work characteristics are also frequently differentiated by race.[3] This is especially valid in many of the large urban areas of the United States where the presence of racial discrimination represents a major market imperfection, which distorts the spatial demand for residential space by both whites and non-whites."[4] Increasingly in these areas, whites flee to the suburbs from neighbourhoods of changing racial

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1 Duncan, "Factors in Work-Residence Separation", p. 57.

2 See for example, Paul K. Hatt, "Occupation and Social Stratification", American Journal of Sociology 55 (May, 1950): 533-43 and J. Reiss et al, Occupations and Social Status, The Free Press of Glenco, New York, 1961.

3 See for example, Duncan, "Factors in Work-Residence Separation" p. 50; Kain, "The Journey-to-Work", p. 145; Hamburg, Journey-to-Work Minimization, p. 74; Voorhees, Factors, Trends and Guidelines, p. 13.

4 Kain, "The Journey to Work", p. 158.

composition in central areas close to their jobs. Meanwhile non-whites, regardless of income, are restricted to living in central city "ghettos" and sometimes must reverse commute to fringe areas to find jobs. On the whole, average separation is usually less for non-whites, and those employed in the suburbs have longer commuting distances than those employed centrally. This is just the reverse of the pattern observed for white commuters.

While racial segregation is generally not as serious a problem in Canada as it is in the United States, there are, nevertheless, ethnically distinct areas in many Canadian cities where residents of similar ethnic origins reside as a group for mutual support and social, cultural, and linguistic accessibility. This is often the case with the Chinese, Italians, French Canadians in English-speaking provinces, and English Canadians in predominently French-speaking areas. This phenomenon represents a major distortion in the housing market and limits the range of suitable residential and sometimes work opportunities for such groups.

Differing average work-residence separations have also been observed for the sexes. In general, women tend to live closer to their jobs than men.[1] There are several possible explanations for this phenomenon. One is that married women are often secondary or part-time wage earners

1 See, Duncan "Factors in Work-Residence Separation" p. 53; Kain, "The Journey-to-Work", p. 146; Fisher and Sosslau, "Census Data" p. 52.

whose commitment to home and family is greater than that of their spouse.[1] As a result, finding a job may not be that critical for them and they can afford to wait and find a job convenient to home. Another possibility is that in families with two incomes, the husband and wife often work in the same general area, and as a result, there is a greater incentive for them to live close to that location. A third possibility relates to the mode of travel employed most often by each sex. Reeder found that worktrip travel times for men and women were not significantly different, however women rely to a much greater extent on public transit, whereas men used private automobiles for the most part.[2] Their dependence on slower public transit may account for a reduced spatial separation between homes and jobs on the part of women workers.

Marital status, life cycle stage and family size are other variables which appear to affect work-residence separation. For the most part these relate to supply and demand for residential space. Fisher and Sosslau found that adults in the 25 to 44 age group tend to travel slightly farther than younger and older groups.[3] This is, no doubt, because of additional demand for residential space during the marriage and child-rearing phase of life and the adoption of a suburban life-style, as suggested by Brown.[4] Increased separation from work also

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1 This tendency to work closer to home would also apply to other secondary wage earners; such as, adolescents, who are still living with their parents. In households with several incomes, residential location is likely to be determined on the basis of proxmity to the job location of the primary wage earner.

2 Reeder, "Social Differentials", p. 60.

3 Fisher and Sosslau, "Census Data", p. 54.

4 Brown, "Changes in Workplace", p. 35.

correlates with family size and income earning power which are usually close to their peaks during the 25-44 age period. Increasing family size results in additional demand for indoor and outdoor residential space while increasing earning power facilitates attaining it. This is only true up to a point however, since Kain observed that families of five persons or more tend to live closer to the center of the city and consume smaller quantities of space, probably because of pressure on a limited income created by providing life's necessities for a large family.[1]

Single persons and couples, either before or after raising children, tend to reside closer to downtown activity centers where suitable apartment accommodation is normally concentrated. As a result their trips to work, often located in the central business district, are slightly shorter than those of suburban commuters.

There are, undoubtedly, a number of other socio-economic factors which might distort or moderate theoretical patterns of work-residence separation. For example, one of these might be subsidization of homes and jobs. Workers, whose homes are provided or subsidized by their employers, inheritors of a family business or dwelling unit, workers in government jobs, and residents of public housing are all cases of households, whose locational decisions are constrained or altered to some degree by the atypical opportunities available to them.

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1 Kain, "The Journey-to-Work", p. 150.

Beyond purely socio-economic considerations, one must consider the psychological characteristics of commuting households and their influence on worktrip length. In the middle ages, it was common practice for craftsmen and artisans to work in the cottages where they lived. Later as a result of the abuses of sweat shop labour during the Industrial Revolution, aversion to daily work became quite commonplace; and when they could, workers put the scene of the day's toil out of sight and out of mind by living apart from it. Even today, there are, undoubtedly, many who see their jobs in this light, and as a result, live farther from their workplace than they otherwise might. On the other hand, there are probably many who are so involved in their work that they find it difficult to separate themselves from it physically, as well as mentally. It would be extremely difficult to assess current attitudes towards work accurately and then predict the resultant impact on worktrip length, but it does seem logical that such factors would play a role in a household's locational decision.

Identification with a particular community or geographic area is another psychological factor which may influence work-residence separation. As mentioned earlier, Keefer found workers reluctant to cross major travel barriers such as river valleys and so lived in disproportionate numbers on the side nearest their place of employment. It may be that identifiable physical barriers not only represent a real time delay in commuting but also constitute psychological barriers or perhaps, just convenient recognizable boundaries, within which workers prefer to confine their commuting activity. Voorhees found that there was an unusually strong reluctance to make worktrips between Minneapolis and St. Paul.[1] He suggests this is due to a strong community identification, not just because of the barrier effect of the Mississippi River separating the two cities, but rather because of their distint identifiable city centers and the impact of each having separate newspapers and other media. In other words, workers more familiar with opportunities in their own community are likely to have both their worktrip origin and destination in that community irrespective of the fact that closer opportunities may be available in adjacent areas. Voorhees suggests that similar travel patterns may be observed in other urban areas with multiple city centers and that this phenomena accounts in part for the need for "socio-economic adjustment factors" to calibrate gravity models so they duplicate observed commuting.

One last psychological factor which might be considered is that which Keefer terms the worktrip "time-space transition".[2] The journey-to-work offers the individual a chance to change mental gears; to plan his work day activities, or slowly unwind. Assuming that this is an integral, and perhaps healthy aspect of commuting, it may subconsciously affect worktrip length according to the amount of time an individual feels he requires to adjust to new environments and activities.

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1 A.M. Voorhees et al "Factors in Work Trip Lengths", Highway Research Record 141 (1965): 34.

2 L.E. Keefer in an appended discussion of A.M. Voorhees et al, "Factors in Work Trip Lengths", Highway Research Record 141 (1965): 40.

The appeal of this opportunity for mental preparation or relaxation is probably represented in the extreme by the cheerful, long-distance, rail commuter, who sees his trip as an opportunity to do additional work, read the paper, play cards, or just socialize with travel acquaintances.

CHAPTER II

ANALYTICAL MODELS OF SPATIAL INTERACTION

Human Interaction and Modelling

The degree of interaction, in terms of communication or travel, between two population concentrations increases as the potential for interaction, or the number of attractive terminal opportunities, in the two locations increases and decreases as the degree of separation between them increases. In the context of the journey to work, this means that a larger volume of worktrips is likely between zones which contain a large number of residential origins and employment destinations and which are convenient to one another.

As shown earlier, empirical evidence also supports the converse of the above relationships in circumstances where a given amount of interaction is essential, as in the case of the worktrip. Over the long term, individuals have control over the location of their trip ends, and they are more likely to locate their home or job in a zone which contains a large number of suitable residential or employment opportunities, and which reduces or limits their work-residence separation.

Over the past century or so, there have been various attempts to mathematically interpret or "model" this basic pattern of human spatial interaction. With respect to tripmaking, these models take the general form:

$$T_{i,j} = T_i \times P(A_j)$$

where: $T_{i,j}$ is the number of trip interchanges between zones i and j;

T_i is the number of trips generated in zone i; and,

$P(A_j)$ is the probability of the destination being in zone j.

The destination term, $P(A_j)$, distributes the trips originating in zone i among the possible destination zones and accounts for both the attractive qualities of zone j as well as the element of impedance due to the spatial separation between i and j. In this configuration, the model is a trip distribution formula. It has been used by social scientists interested in analyzing and predicting social and commercial interaction, particularly migration flows. More recently, it has been used by transportation planners to predict zone to zone movements as an intermediate step in determining design traffic volumes for specific transportation facilities.

The fundamental spatial interaction relationship may also be cast in a residential location or growth allocation format. These models may be considered to take the general form:

$$R_{i,j} = D_i \times P(S_j)$$

where: $R_{i,j}$ is the number of residences in zone j belonging to workers employed in zone i;

D_i is the total demand for residences of workers employed in zone i; and,

$P(S_j)$ is the probability of a suitable residence being supplied in zone j.

The residential supply term, $P(S_j)$, allocates the demand for residences of workers employed in zone i among the possible residential supply zones and usually accounts for the attractive residential qualities of zone j as well as the commuting impedance between i and j. Over the past few decades, this type of formulation has been employed by location theorists and urban planners as a means of analyzing and predicting the residential distribution of workers around employment centers. Given that the location of industrial and commercial employment centers is to a large degree limited by transportation facilities, economic, and other relatively permanent and predictable factors, if a satisfactory formula for distributing population growth with respect to assumed future employment centers is available, it is possible that useful generalized urban land use models may be derived.[1]

The ultimate objective of spatial interaction modelling efforts is usually to come up with a formula which reconciles a requirement for simplicity and economy, in terms of the input data and calculation necessary, with a desire for a correct mathematical interpretation of underlying causal relationships. Such a model might be termed analytic as opposed to synthetic in nature.

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1 H. Blumenfeld, "Are Land Use Patterns Predictable?" Journal of the American Institute of Planners, 25 (May 1959): 64.

Several synthetic interaction models have been built upon growth factor, expansion, or trend projection methods, as well as various curve fitting techniques such as multiple regression analysis. Such models are useful in the absence of more analytic formulations and have helped to explore the importance of the various factors involved. However, they are normally very empirical in nature with large imput data requirements, and they are not very intuitively satisfying. Generally, any agreement between observed and predicted levels of interaction is not because the model represents the underlying forces at work but rather because it is formulated and amended almost by trial and error to handle numbers so that agreement is reached.

The same has been said of some of the more analytical models of spatial interaction derived by analogy with physical phenomena. Recently however, such models have been refined and given a firmer theoretical base through derivation from elementary probability and statistical theory. Models of this nature fall into two basic types, the Gravity Model and the Opportunity Model.

The Gravity Model

The earliest known explicit formulation of the gravity concept of human interaction was made by H.C. Carey during the first half of the 19th Century. He stated:

> Man the molecule of society is the subject of Social Science . . . The great law of Molecular Gravitation (is) the indispensible condition of the existence of the being known as man . . . The

greater the number collected in a given space, the greater is the attractive force that is there exerted . . . Gravitation is here, as everywhere, in the direct ratio of the mass and the inverse one of distance.[1]

The applicability of the physical law of gravity to human interaction was subsequently indicated in early partial formulations by E.H. Ravenstein (1885) and E.C. Young (1924) based on empirical migration evidence, as well as by W.J. Reilly based on evidence of retail trade area influence.

In the 1940's, J.Q. Stewart and G.K. Zipf generalized the gravity concept by returning to the original formulation in terms of Newtonian Physics, namely that the "force" of interaction between two concentrations of population, acting on a line joining their centers, is directly proportional to the product of the populations of the two centers and inversely proportional to the square of the distance between them. Mathematically, this yields:

$$F_{i,j} = \frac{P_i \, P_j}{D_{i,j}^{\,2}}$$

where $F_{i,j}$ is the force of interaction between concentrations i and j.

1 H.C. Carey, Principles of Social Science (Philadelphia: J.B. Lippincott and Co., 1858-59) as quoted in G.A.P. Carrothers "An Historical Review of the Gravity and Potential Concepts of Human Interaction", Journal of the American Institute of Planners 22 (Spring 1956): 94.

Following the analogy from physics the energy of interaction between the two centers resulting from this force would be:

$$E_{i,j} = \frac{k\ P_i\ P_j}{D_{i,j}}$$

where $E_{i,j}$ is the energy of interaction, and k is a constant of proportionality, equivalent to the gravitational constant of physics.

Zipf, Stewart and others tested this formulation empirically, measuring the energy of interaction between pairs of cities by a variety of characteristics such as telephone calls, bus passenger movements, newspaper circulation and the like.[1]

The distance factor in the gravity concept has been a source of considerable debate. Several researchers have suggested that the impact of distance is not uniform and its relationship in the basic equation is not a simple inverse one, but one in which distance is raised to some power other than unity. Various exponents from one half to over three have been empirically tested. T.R. Anderson has suggested that the exponent is itself a variable, inversely related to the population of the attracting center.[2] On the other hand, J.A.P. Carrothers suggested that the exponent may be an inverse function of distance itself, since the impedance per unit of distance against interaction caused by short

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1 Cited in Carrothers, "Review", p. 95.

2 T.R. Anderson "Intermetropolitan Migration: A Comparison of the Hypotheses of Zipf and Stouffer, "American Sociological Review 20:33 (6/55): 291.

distances seems disproportionately greater than the impedance per unit of distance for longer distances.[1]

Stewart and S.C. Dodd also suggested modification of the numerator of the basic equation to account for certain areas where the population seemed to exert an undue influence on interaction.[2] They added multipliers to the population variables to account for these observed differences in influence resulting from differences in population characteristics. They interpreted the multipliers to be a measure of a particular population's capacity for interaction.

In the middle 1950's, A.M. Voorhees began applying the gravitational principle to traffic analysis.[3] This initiated an important chapter in the development of the gravity model in which it was repeatedly tested on the masses of data collected in metropolitan traffic origin and destination surveys. Voorhees used time of travel as the most meaningful measure of travel separation and classified movement by mode of travel to account for differing speeds. At the same time he suggested classifying trips according to their purpose or destination and began measuring the attractive influence of the destination in terms of population, employment or retail sales floor area.

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1 Carrothers, "Review", p. 97.

2 Cited in Carrothers, "Review", p. 97.

3 Alan M. Voorhees, "A General Theory of Traffic Movement", Proceedings, Institute of Traffic Engineers, (1955) pp. 46-56.

Voorhees' early formulation of the gravity model is:

$$T_{i,j} \propto T_i \left[\frac{A_j}{D_{i,j}{}^x} \right]$$

where $T_{i,j}$ is the number of one-way trips from origin zone i to destination zone j;

T_i is the number of trips generated at origin zone i;

A_j is the measure of attraction for zone j;

$D_{i,j}$ is the impedance between zones usually in terms of travel time; and

x is an exponent to which $D_{i,j}$ is raised which varies according to trip purpose.[1]

Accounting for the element of proportionality above the model becomes for the whole region:

$$T_{i,j} = T_i \left[\frac{\dfrac{A_j}{D_{i,j}{}^x}}{\sum\limits_{j \neq i} \dfrac{A_j}{D_{i,j}{}^x}} \right]$$

The value for x for each trip purpose is determined through a calibration process where predicted interchanges using a trial exponent are compared with actual interchanges from the origin-destination survey and

1 Usually the exponent decreases as the trip purpose becomes more important and is lowest for work trips indicating that people are willing to travel further to work than for other purposes.

appropriate adjustments made. In actual operation, the model must also be iterated to ensure convergence of the predicted total trips attracted to a given zone from all other zones with the actual total attractions.[1]

Since the values, adopted for A_j and x, are based on a study of existing land uses and trip purposes, this model may be considered somewhat analytic. It is still, nonetheless, a synthesized model of traffic behavior, albeit one based on a careful analysis of existing relationships.

Besides the important consideration of whether or not model parameters estimated from an existing situation will hold good for future prediction purposes, Voorhees' model has a number of other shortcomings. One of these is that the model is valid only for the city in which it was calibrated. In different cities the value of x determined for a given trip purpose was found to vary considerably, consequently the model is not transferable and a comprehensive origin-destination survey is required for each city in which it is applied.

There is also considerable debate as to whether or not a single impedance exponent, which in fact represents an average for an entire metropolitan area, is applicable to movements between individual zones. A number of other researchers have empirically computed different friction factors for each zone pair and obtained better conformity with observed

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1 The model equation itself ensures that predicted zonal generation will equal actual generation.

data. The variation in impedance factors appears related to variation in land use and employment opportunities, especially with respect to location relative to the Central Business District. Voorhees found preliminary evidence that nearby activities were incorrectly more heavily-weighted by the gravity model as spatial opportunities arranged themselves at greater mean opportunity times from a particular zone.[1] He suggested that the impedance factor may have to be modified to account for variations in the opportunity distribution.

The conventional method of handling the problem outlined above, and a variety of other discrepances between prediction and observation in large metropolitan areas, has been the introduction of zone to zone socio-economic adjustment factors in the numerator of the gravity model, which then becomes:

$$T_{i,j} = \frac{T_i \; A_j \; F_{i,j} \; K_{i,j}}{\sum_{j=1}^{n} (A_j \; F_{i,j} \; K_{i,j})}$$

where $F_{i,j}$ is a generalized impedance factor, originally of the form

$F_{i,j} = D_{i,j}^{-x}$, and

$K_{i,j}$ is a zone to zone socio-economic adjustment factor.

The $K_{i,j}$ term is empirically derived based on the ratio between origin-destination survey results and preliminary gravity model results. It

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1 Voorhees et al, "Factors in Work Trip Lengths", p. 29.

may, in fact, be considered an error term, which accounts for unique travel situations not already accounted for in the model. There have been a variety of reasons put forward as to why such a factor is necessary. One is that trip purpose stratifications used are not precise enough. For example, all work trips produced by a particular zone may in reality be made by industrial workers, and when distributed by the gravity model, the largest proportion of these would be sent to nearby employment centers regardless of whether or not the employment there was industrial in nature. Related to this is the suggestion that high income groups have a greater propensity or ability to travel, and, therefore the population of zones with unusually high incomes might travel further than normal to their places of work, shopping or recreation.[1] Another suggestion is that particular zones have strong ties by virtue of the timing of their development, historical community identification, or media-generated opportunity awareness.

The conventional form of the gravity model resistance factor, $F_{i,j} = D_{i,j}^{-x}$, also presented problems. It did not give a good fit with observations, when particularly short or long, trips were involved. Since $F_{i,j}$ approaches infinity as $D_{i,j}$ approaches zero, the value of x is strongly dependent upon the sizes of the zones into which a city is divided.[2] In

1 One might note that K-factors bear some resemblance in form and purpose to the population multipliers used earlier by Stewart and Dodd.

2 John T. Lynch et al, "Panel Discussion on Inter-Area Travel Formulas", Highway Research Board Bulletin 253 (1960): 136.

1962, considerable research was done in Toronto on possible alternative impedance factors.[1] It was found that an exponential function of the form:

$$F_{i,j} = \alpha e^{-\beta D_{i,j}}$$

where e is the base of the natural logorithm, and

α and β are empirically derived parameters,

gave the best fit with data and was mathematically well-behaved.[2] Later work has confirmed the general validity of this finding and a majority of subsequent modeling efforts have used exponential functions in the impedance factor.

Besides the difficulties mentioned above, a frequent complaint against the gravity model is that a concept of applied physics is being used to describe human behavior. Intuition suggests that it should be possible to develop an interaction model, which is somehow more fundamentally related to actual behavior. The development of the opportunity model offered a response to this criticism.

The Opportunity Model

The intervening opportunities model, or more simply the opportunity model, was first conceived by a sociologist, Samuel A. Stouffer, in the 1930's. It assumes that:

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1 K.H. Dieter, "Distribution of Work Trips in Toronto", Journal of the American Society of Civil Engineers 88, CPI (August 1962): 9-28.

2 $F_{i,j}$ varies between one and zero as $D_{i,j}$ varies between zero and infinity.

> ...there is no necessary relationship between mobility and distance. Instead, it introduces the concept of intervening opportunities. It proposes that the number of persons going a given distance is directly proportional to the number of opportunities at that distance and inversely proportional to the number of intervening opportunities.[1]

Mathematically, Stouffer expressed this as:

$$\frac{\Delta Y}{\Delta S} = \frac{a}{X} \frac{\Delta X}{\Delta S}$$

where ΔY is the number of persons moving from an origin to a circular band zone ΔS;

ΔS is the width of the circular band with an inner boundary $S + \Delta S/2$ units of distance from the origin, and outer boundary $S + \Delta S/2$ units from the origin;

ΔX is the number of opportunities within ΔS;

X is the number of intervening opportunities, that is the accumulated opportunites between the origin and distance S; and,

a is a constant of proportionality.

Stouffer and others tested his interaction model on intracity and intercity migration data and generally found that agreement between observed and predicted levels of migration were encouraging.[2]

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1 Samuel A. Stouffer, "Intervening Opportunities: A Theory Relating Mobility and Distance", American Sociological Review 5 (December 1940): 846.

2 See for example, Margaret L. Bright and Dorothy S. Thomas, "Interstate Migration and Intervening Opportunities", American Sociological Review 6 (December 1941) 773-783; Eleanor C. Isbell, "Internal Migration in Sweden, and Intervening Opportunities", American Sociological Review 9 (December 1944) 627-639; and, Fred L. Strodbeck,"Equal Opportunity Intervals: A Contribution to the Method of Intervening Opportunities Analysis", American Sociological Review 14 (August 1949): 490-497.

The opportunity model views migration, or any sort of interaction for that matter, as people choosing among alternative opportunities rather than as a mass of population overcoming the impedance of distance, and as such it is more analgous to actual human behavior. It does not specify a direct and invariant relationship between interaction and distance. Any relationship which does exist is dependent upon an auxiliary relationship expressing intervening opportunities as a function of distance.[1]

It should be clear that the definition of what constitutes a suitable opportunity is critical to the success of the model. In order for opportunities to be considered competitive, they must be essentially similar. In practice, normal sources of data do not permit a definition which is that precise, and proponents of the model tend to use this as an excuse for discrepancies between observation and prediction.

It should also be recognized that for an opportunity to intervene, or be considered, there must be prior knowledge of its existence. This is dependent upon the level of communication in the area which is itself a function of opportunities and distance.[2]

The intervening opportunities concept was first applied to trip distribution by Morton Schneider working in Chicago in the late 1950's.

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1 This auxiliary relationship is similar to the opportunity distribution developed by Voorhees and referred to in Chapter I.

2 Operation of the gravity concept may also be considered dependent upon information exchange in that the traveller must be aware of the attractions, or opportunities, available in the destination zone.

Schneider's formulation was considerably different from Stouffer's and included the notion of probability for the first time. He postulated that:

> . . . the probability that a trip will terminate within some volume of destination points is equal to the probability that the volume contains an acceptable destination, times the probability that an acceptable destination closer to the origin of the trip has not been found.[1]

Since the probability of termination will depend on the distribution of the volume of destination points, the mathematical statement in terms of limitingly small quantities is:

$$dP = (1 - P)\, L\, dV$$

where P is the probability that the trip has terminated within the destination volume, V, lying earlier in the order of consideration and, L is the probability of destination acceptability at the point of consideration.

If L is assumed to be constant for specific kinds of trips or trip purposes, then integrating the above yield:

$$P(V) = 1 - e^{-LV}$$

Thus the probability of a trip terminating in zone j is:

$$P(V+V_j) - P(V) = e^{-LV} - e^{-L(V+V_j)}$$

And the expected trip interchange between zones i and j is:

$$\bar{V}_{i,j} = V_i \left[e^{-LV} - e^{-L(V+V_j)}\right]$$

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1 Chicago Area Transportation Study, Final Report, Vol. II, July 1960, p. 111.

Schneider's method was extensively tested for Chicago and Pittsburgh data and was thought to show an accuracy and reliability for predicted trips as high or higher than the gravity method.[1] It also required less adjustment to fit the model to observed data, although the difficulty in determining the correct L-factor for particular purposes was somewhat comparable. Unlike the gravity model impedance parameter, a separate value of L may be computed for different origin zones, so it is possible to apply the formula successfully to smaller areas. However, the opportunity parameter, like that of the gravity model, is peculiar to the empirical data from which it is derived and not directly transferrable to other cities.

In practice, the L value is determined by taking the logarithm of the basic equation to obtain the linear relationship:

$$-LV = \ln\left[1 - P(V)\right]$$

Once surveyed trip origins for a given zone are arranged in travel time order, empirical values for V and 1-P(V) can be plotted semi-logarithmically to obtain L, the slope of the resulting line. The L-factor can also be estimated from other observed or assumed trip parameters such as the average trip length and then adjusted by trial and error to obtain a satisfactory fit.[2]

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1 It was also found that intervening opportunities as opposed to distance appeared to control the length of urban trips in London, England as cited in Colin Clark and G.H. Peters "The 'Intervening Opportunities' Method of Analysis", Traffic Quarterly 19 (January 1965): 118.

2 Earl R. Ruiter, "Toward a Better Understanding of the Intervening Opportunities Model", Transportation Research 1 (1967): 51-55.

L may be interpreted as a measure of selectivity or as the probability per individual opportunity of destination acceptance. Since Schneider's model considers all destinations, not just those which are predetermined to be suitable, it is the means of discriminating acceptable trip ends according to zone of origin and trip purpose. Normally, empirically determined L values are small, much less than one, and since people are more selective in choosing a residence or place of work than a place to buy groceries, L values for these purposes are smaller and resulting trip lengths greater.

If one were able to specify suitable opportunities precisely enough beforehand, the value of L could be considered equal to one. This permits an interesting comparison between Stouffer's formulation which for limitingly small quantities can be considered to be:

$$dP = V^{-1}\, dV$$

and Schneider's, which can be written as:

$$dP = e^{-V}\, dV.$$ [1]

This is seen to be analogous to the development of exponential forms for the impedance factor of the gravity model where intervening trip volumes replace time-distance as a measure of separation. Once again, the exponential form has better mathematical properties since P(V) varies

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1 The use of derivatives implies the existence of a continuous function, which is not the case, since destinations are discreet entities; however, if V is large, a continuous function can be approximated.

between zero and one, as V varies between zero and infinity. It also means that Schneider's model can be successfully applied to an unbounded region.

In order to avoid the necessity for an adjusting parameter such as L and to apply basic probability theory more directly, Anthony R. Tomazinis developed an alternative competing opportunities trip distribution model, which was applied to Philadelphia and Camden in the Penn-Jersey Transportation Study.[1]

In Tomazinis' model, opportunities are equated with suitable land use destinations obtained from trip generation studies. With reference to Figure 6, the total universe of such opportunities in a bounded region is denoted by N. A subpopulation H is chosen which consists of all opportunities bounded by the areal equivalent of the travel time distance between an origin zone I and destination zone J. The probability of a trip ending in zone J, a part of subpopulation H, is then given by the conditional probability of randomly selecting a destination opportunity in J from N, which is at the same time an opportunity randomly selected in H from N, or:

$$P(S_j) = P(J/H) = P_{JH}/P_H = \frac{J/N}{H/N} = J/H$$

where $P(S_j)$ is the probability of stopping in zone J;

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1 Anthony R. Tomazinis, "A New Method of Trip Distribution in an Urban Area" Highway Research Board Bulletin 347 (1962): 77-99.

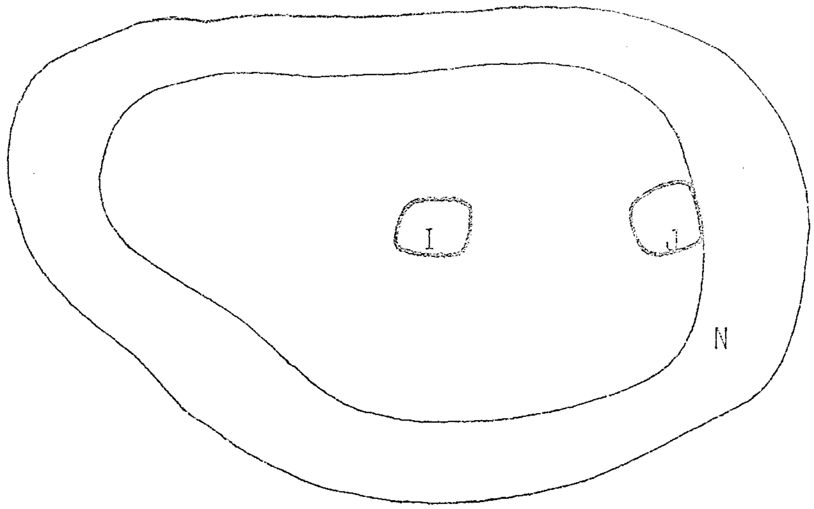

Figure 6: Selection of a Travel Time Bounded Subpopulation of Destination Opportunities from the Universe Around an Origin. (Source: Tomazinis, "New Method of Trip Distribution", p. 79.)

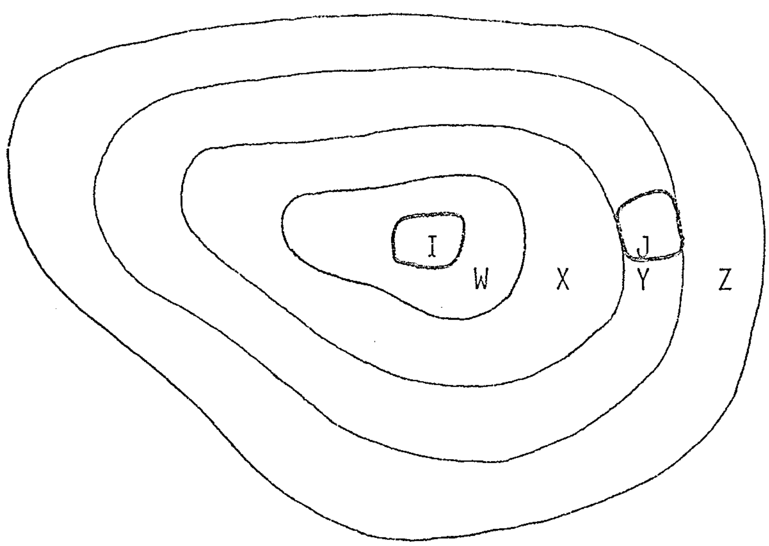

Figure 7: Designation of Equal Time-Distance Intervals About an Origin. (Source: Tomazinis, "New Method of Trip Distribution", p. 80.)

J is the opportunity subpopulation in destination zone J;

H is the opportunity subpopulation within travel time district H; and

N is the total universe of competing opportunities.

If the region is divided into a number of concentric equal time distance bands, as in Figure 7, then the probability expressed above is given by:

$$P(S_j) = \left[\frac{Y}{W+X+Y}\right]\left[\frac{J}{Y}\right]$$

where W+X+Y=H; and

W+X+Y+Z = N

After computing $P(S_j)$ for every destination zone and then normalizing them such that:

$$P'(S_j) = 1$$

then the trip interchange is given by:

$$T_{i,j} = T_i \times P'(S_j)$$

where T_i is the total number of trips generated at origin zone I;

and,

$P'(S_j)$ is the normalized probability of a trip stopping in in destination zone J.

In an application to later data, Tomazinis found that his model predicted well, given its stochastic nature, but it tended to over-estimate longer trips. To adjust for this, he introduced the concept of the probability of satisfaction, which he defines to be the ratio of trip destinations outside of the time district being considered to the total destinations in the region. In the case of Figure 7, this would be:

$$\frac{Z}{W+X+Y+Z}$$

$P(S_j)$ is now defined to be the product of the probability of the district P(Y) and the probability of satisfaction or:

$$P(S_j) = \left[\frac{Y}{W+X+Y}\right] \left[\frac{Z}{W+X+Y+Z}\right] \left[\frac{J}{Y}\right]$$

Tomazinis model avoids the use of an empirically-derived parameter and is relatively simple to employ. It dispenses with the need for expensive calibration manipulation and is, in theory, directly transferrable to other cities. It also appears to have a firm basis in probability theory, although the fact that initial $P(S_j)$'s do not add to one and the necessity for a "probability of satisfaction" are intuitively disturbing.

If the opportunities considered are in any sense to be competitive or "randomly selected" their designation must be suitably precise. If trip generation data available does not permit this, then the use of an adjustable parameter may be attractive, so that observed travel patterns can be duplicated.

The model might be also criticized on the grounds that it must be applied to a bounded region, and because opportunities closer to the origin within a particular time-distance district are more likely to be selected, its potential accuracy depends on the level of time-distance aggregation actually used. Because of perception limitations on the part of the travelling public, a travel-time interval of five minutes is probably the minimum that can be employed.[1]

The Entropy-Maximizing Model

In the late 1960's, Alan G. Wilson applied the statistical concept of entropy maximization to the derivation of interaction models, especially the gravity model, and in so doing has produced a "family" of models with a firm theoretical basis.[2] Entropy here is considered to be a statistical measure of uncertainty or ignorance, and it will be shown that to maximize entropy in a system is to make the maximally unbiased estimate about the state of a system subject to whatever is known about it.

The true state of any particular system may be considered the most complete or detailed specification of the system or its microstate, such as the number of dots showing on each of two tossed dice. Any aggregate specification of the system may be termed a macrostate, such as the sum of the dots showing on the dice. Given only macrostate information, a blind man would still be uncertain about the true microstate of the system, but his uncertainty would be reduced to some degree; since a

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1 The realities of zonal aggregation and travel time perception are not usually imposed on the gravity model, although the statements, made above, are just as applicable to it.

2 Alan G. Wilson, "A Statistical Theory of Spatial Distribution Models", Transportation Research 1 (1967): 253-269.

particular sum is only achievable in a limited number of ways among all of the possible combinations or microstates of the two dice.

If we let w_i be the number of ways, or microstates, in which a particular macrostate can be achieved, as w_i increases, uncertainty with respect to the actual microstate increases. Any monotonic function of w_i can be defined to represent this increasing uncertainty or "entropy". Normally,

$$S_i = k \ln (w_i)^1$$

where S_i is a measure of entropy, and

k is an arbitrary constant.

If all microstates were equally probable for a given macrostate, we could write the probability of a particular microstate as:

$$p_i = 1/w_i$$

and the entropy equation would be:

$$S_i = -k \ln (p_i)$$

Usually, we do not know for sure that all microstates are equally likely, but the maximum entropy principle dictates that in the absence of other

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1 Other monotinic functions could be employed, but entropy for compound events is additive where a logarithmic function is used and, $S_i = 0$ when there is complete certainty or $w_i = 1$.

information, we should give the microstate probabilities equal weight and assume that the outcome, which can occur in the greatest number of ways, is the outcome with the highest probability of occurrence. In other words, we assume the broadest, flatest probability distribution possible, consistent with given information. Any additional, but not perfect, information is incorporated as constraints in the process of maximizing the entropy equation, thereby obtaining the maximally unbiased estimate of the state of the system.

The entropy concept can now be applied to the development of a spatial interaction model. For example, we may wish to find the matrix of trip interchanges, $\{t_{i,j}\}$, for the journey to work during the morning peak hour, which is maximally noncommitted and unbiased, consistent with the information at our disposal. Assuming the total number of trips emanating from each origin, O_i, and the number of trips terminating at each destination, D_j, are given exogenously we have:

$$O_i = \sum_{j=1}^{m} t_{i,j}$$

$$D_j = \sum_{i=1}^{n} t_{i,j}$$

and

$$T = \sum_{i=1}^{n} O_i = \sum_{j=1}^{m} D_j = \sum_{i=1}^{n} \sum_{j=1}^{m} t_{i,j}$$

where T is the total number of travellers in the system.

If each of the T individuals could be identified, a microstate in this case would be an enumeration of who travels where. A macrostate, on the other hand, would merely specify how many people travel between i and j, that is $\{t_{i,j}\}$ without regard for individual identification. By applying the combinatorial formula of statistics, it can be shown that the total number of ways in which a particular distribution $\{t_{i,j}\}$ can be selected from T travellers is :

$$W = \frac{T!}{\prod_{i}\prod_{j} t_{i,j}!}$$

and

$$S = k \ln\left(\frac{T!}{\prod_{i}\prod_{j} t_{i,j}!}\right)$$

Incorporating constraints, the entropy lagrangian to be maximized becomes:

$$L = \ln\left(\frac{T!}{\prod\prod t_{i,j}!}\right) + \sum_{i} \lambda_i^{(1)}(O_i - \sum_{j} t_{i,j}) + \sum_{j} \lambda_j^{(2)}(D_j - \sum_{i} t_{i,j}) + \beta(C - \sum_{i}\sum_{j} t_{i,j}\, c_{i,j})$$

where $\lambda_i^{(1)}$, $\lambda_j^{(2)}$ and β are the Lagrangian multipliers.

Note that a third constraint has been introduced:

$$\sum_{i}\sum_{j} t_{i,j}\, c_{i,j} = C$$

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1 This and an alternate method of selecting travellers associated with particular origins which produces the same results are illustrated in Frank J. Cesario, "A Primer on Entropy Modelling", Journal of the American Institute of Planners 41 (January 1975): 40-48.

where $c_{i,j}$ is the impedance or generalized cost of travelling between origin i and destination j; and,

C is a fixed total expenditure spent on trips in the regions at any given time.

Now the $t_{i,j}$'s, which maximize the entropy Lagrangian, L, and therefore constitute the most probable distribution of trips are given by the solution of:

$$\frac{\partial L}{\partial t_{i,j}} = 0$$

and the constraint equations. It can be shown that this yields:

$$t_{i,j} = A_i\, B_j\, O_i\, D_j\, e^{-\beta c_{i,j}}\ ^{1}$$

$$A_i = \left[\sum_j B_j\, D_j\, e^{-\beta c_{i,j}}\right]^{-1}$$

and

$$B_j = \left[\sum_i A_i\, O_i\, e^{-\beta c_{i,j}}\right]^{-1}$$

where

$$A_i = \frac{e^{-\lambda_i^{(1)}}}{O_i} \quad \text{and} \quad B_j = \frac{e^{-\lambda_j^{(2)}}}{D_j}$$

This is recognized as the familiar gravity model and so this statistical derivation constitutes a new theoretical basis for it. It should be noted that C in the impedance cost constraint equation need not actually be known since the β - parameter can be found by the usual

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1 Wilson also shows the maximum obtained is a very sharp one and, therefore the distribution $\{t_{i,j}\}$ obtained is overwhelmingly the most probable in "Statistical Theory", pp. 258-260.

calibration methods. Where the solution is origin and destination constrained, as above, A_i and B_j must be determined iteratively as well.

Without constraints, the entropy-maximizing derivation employed above would have resulted in all $t_{i,j}$'s having an equal number of trips, so it is the constraints which produce trip distributions other than trivial ones. It is possible then to analyse and refine the spatial interaction model by systematically altering the constraints applicable to behavioural variables. This enables derivation of a family of related models. The fairly straight-forward refinement process employed is a major achievement of Wilson's application of entropy maximization to interaction modelling.

The trip distribution model, outlined above, was constrained with respect to both the production and attraction of trips at origin and destination zones. If D_j is replaced by W_j, some index of attractiveness, not necessarily trip ends and we use only;

$$\sum_j t_{i,j} = O_i$$

we obtain a model, which is only production constrained:

$$t_{i,j} = A_i \, O_i \, W_j \, e^{-\beta c_{i,j}}$$

where $$A_i = \left[\sum_j W_j \, e^{-\beta c_{i,j}} \right]^{-1}$$

The equation;

$$\sum_i t_{i,j} = W_j \sum_i A_i \, O_i \, e^{-\beta c_{i,j}}$$

now provides an estimate of trip ends at j, and since trip ends are an index of activity by location, it can be used as an activity location model. For example, it could be used to estimate the location of retail activity for a given population distribution where origin zone retail expenditure determines the equivalent of O_i, and W_j is the retail sales floor area at destination zone j.[1]

Similarily, it is possible to obtain an attraction constrained model where D_j's but not O_i's are given externally. In this case,

$$t_{i,j} = B_j \, W_i \, D_j \, e^{-\beta c_{i,j}}$$

where

$$B_j = \left[\sum_i W_i \, e^{-\beta c_{i,j}} \right]^{-1}$$

and W_i is an index of attractiveness associated with origin zone i.

This may be developed into a residential location model:

$$\sum_j t_{i,j} = W_i \sum_j B_j \, D_j \, e^{-\beta c_{i,j}}$$

where residential activity can be allocated, according to the residential attractiveness of origin zones, W_i, and a given employment distribution in destination zones, D_j.[2]

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1 See, T.R. Lakshmanan and Walter G. Hansen, "A Retail Market Potential Model" Journal of the American Institute of Planners 31 (1965): 134-143.

2 Alan G. Wilson, "Developments of Some Elementary Residential Location Models", Journal of Regional Science 9 (1969): 380.

Wilson has suggested that the relationship between these three models might be exploited by linking them into a quasi-dynamic forecasting system.[1] The residential location model and trip distribution model, for example, each produce different estimates of the journey to work, but if O_i and D_j are given, the doubly-constrained model best reproduces survey year data. Its use in forecasting is, however, limited by the reliability of independent forecast year trip and estimation. It may be possible to use the location model version to allocate pools of potential movers, a time period at a time, and then use the accumulated output for the forecast year as input to a trip distribution process, employing the doubly-constrained version. The common heritage of Wilson's family of models has thus been a stimulus leading to the development of more dynamic interaction models.

The characteristrics of the singly-constrained models outlined above also assist in the interpretation of the recurring terms A_i and B_j. In the production-constrained model, A_i is a competition term which reduces most trips due to the increased attractiveness of any one zone. The denominator of A_i or,

$$\sum_j W_j \, e^{-\beta c_{i,j}}$$

is commonly interpreted as a measure of total accessibility which increases as travel times or costs decrease and attractiveness increases for destination zones. It can also be interpreted as a measure of the

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1 Alan G. Wilson, "Advances and Problems in Distribution Modelling" Transportation Research 4 (1970): 12.

competition that shops in j face from other retail centres as perceived from i, in the retail activity location context. The model term,

$$\frac{W_j \, e^{-\beta c_{i,j}}}{\sum_j W_j \, e^{-\beta c_{i,j}}}$$

is then a measure of the relative accessibility-attractiveness of j perceived from i. The B_j-parameter can be given a similar balancing factor interpretation in the attraction-constrained model, where it adjusts for the increased emissivity of any particular origin zone. In a production and attraction-constrained model, it is impossible to write both A_i and B_j independently, since both are acting together simultaneously. However, A_i^{-1} is related to the accessibility of opportunities at the destination end of a trip as perceived from origin i, and B_j^{-1} is related to the accessibility of opportunities at the origin end as perceived from destination j.

Thus far, we have dealt with the origin and destination trip total constraints. It is now time to consider Wilson's third constraint. He claims that the preferred negative exponential form of the impedance function in his deviation of the gravity model arises because of the nature of the generalized cost constraint equation,

$$\sum_i \sum_j t_{i,j} \; c_{i,j} = C$$

which assumes that people perceive costs subjectively in the same way that they are measured objectively.[1] Alternatively, it can be argued that people perceive costs in a way in which the same marginal distance on a long trip is valued less than on a short trip. In this case, Wilson feels it would be appropriate to substitute $\ln(c_{i,j})$ for $c_{i,j}$ in the constraint equation. The interaction model impedance function would then become $c_{i,j}^{-\beta}$ instead of $e^{-\beta c_{i,j}}$. He suggests it would be appropriate to use this modification for interurban analyses where longer trips become involved.

Wilson's argument that an exponential travel deterence function is an inexorable result of the choice of a cost constraint is not totally convincing. The result has at least as much to do with the choice of $\ln w_i$, as a mathematically convenient entropy function. The fact that Wilson makes no conscious attempt to duplicate the negative exponential decay of travel with increasing distance observed in most North American cities is the basis of Curry's criticism that Wilson is using a "posterior form of analysis".[2] In other words, one cannot use ones intuition about travel behaviour to derive the entropy maximizing model. It is only the result of the derivation, which can be given a behavioral interpretation.

As in the case of previous interaction models, the interpretation and stability of the β-parameter in the deterence function is also a matter of concern. β is inversely related to the average distance travelled

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1 Wilson, "Advances and Problems", p. 8.

2 L. Curry, "A Spatial Analysis of Gravity Flows," Regional Studies 6 (1972): 134.

and the total travel expenditure in a region. In fact, β is approximately equal to the inverse of the mean expenditure or distance travelled. Consequently, it may be used as to provide a first estimate for β in the model calibration process.[1] β may also be viewed as an inverse measure of propensity to travel. If β decreases, longer trips are more likely; whereas if β increases, smaller $c_{i,j}$'s will be weighted more heavily.

As suggested earlier, β has been found to be sensitive to the distribution of destinations about the zone of origin. That is to say, β decreases as the distance of the trip origin from the Central Business District or the largest employment centre increases or alternatively as the mean opportunity spacing increases. Therefore, β-parameters should be origin-specific. This disaggregation can be achieved by employing an origin zone cost constraint equation of the form:

$$\sum_j t_{i,j} \; c_{i,j} = C_i$$

The impedance function then becomes:

$$e^{-\beta_i \, c_{i,j}}$$

where β_i is obtained by iteration for each origin.

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1 C. Fisk and G.R. Brown, The Role of Model Parameters in Trip Distribution Models Transportation Research 9 (1975): 144.

Wilson suggests that a possible theorectical basis for this procedure is that β_i decreases as the average income of travellers increases.[1] Average income, in turn, usually increases with distance from the Central Business District. Since it appears that travellers are not as deterred by cost or travel time as opportunity spacing increases, an equally plausible explanation is that urban travel is controlled more by the distribution of opportunities, as proposed in the Opportunity Model, than cost or travel time per se.

Fisk and Brown suggest that the assumption adopted in present model applications that the β-parameters remain constant between base and prediction years is not justified.[2] Changes in β_i between base and prediction years will depend on perturbations in average zonal expenditures or travel time caused by changes in the attractiveness of destination zones (or the opportunities available there), specific zone-to-zone travel times, and other variables not explicitly contained in the model but which may affect travel behaviour.[3]

Given the possibility of the important role of opportunities, suggested above, Wilson also attempts to derive Schneider's intervening opportu-

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1 Alan G. Wilson, "A Family of Spatial Interaction Models and Associated Developments", Environment and Planning 3 (1971): 18.

2 Fisk and Brown, "Role of Model Parameters", p. 144.

3 The apriori assumption of equal probabilities for all possible trip arrangements used in entropy maximizing may be wrong due to bias in destination choice arising from unspecified socio-economic considerations. If such bias is measurable, it may be incorporated into the model as before through the use of $K_{i,j}$- factors within the statistical mechanical formalism of an objective interpretation of probability theory. ibid.

nities model using entropy maximization. He succeeds, but it is at the expense of using intervening opportunities as a rather strange proxy for travel expenditures in the third constraint. The opportunities passed contribute to the cost associated with each trip interchange weighted by the number of times they have been passed or have intervened. This procedure is intuitively suspect and Wilson suggests that this may be enough in itself to prefer the gravity model.[1] However, one wonders if other, more satisfying, opportunity constraints might not be devised, and incorporated successfully into an entropy maximizing formulation.

Although the opportunity model is apparently not readily amenable to the entropy maximizing approach, it has enabled the extension of the gravity model to realistically represent more complex travel situations and permitted the application of economic evaluation techniques to changes in policy variables. This has been achieved largely through systematic disaggregation of variables and the use of subscripts and superscripts on parameters to achieve internal consistency. Wilson has thus far successfully disaggregated the basic models with respect to trip purpose, mode of travel, routes, impedance cost characteristics, and traveller characteristics such as car ownership, income, and origin location. Additional constraints have been added as policy decisions to handle limitations on destination zone parking capacity, route-capacity, population density and the input/output flow of goods.

A major benefit of this disaggregation effort has been the possibility of systemic integration of all of the traditional steps in the trans-

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1 Wilson, "Statistical Theory", p. 268.

portation planning process. Trip distribution, modal split, route assignment and even trip generation in the form of category analysis, all focus on one basic interaction equation and can be forecast in a single operation. This is, however, at the limit of the extent of disaggregation which can be achieved. Eventually, the number of model parameters which must be estimated increases to uncomfortable proportions and there is the risk of losing statistical relevance as disaggregated flows get smaller.

As an alternative to disaggregation of probability or statistical approaches as a means of improving the behavioural basis of interaction models, Wilson suggests bringing matters down to the level of the individual decision-maker by applying the theory of consumer behaviour. This assumes that individuals in the population have preference structures and exercise travel choices which can be seen as the result of maximizing personal utility functions subject to budgetary and time constraints.

The major difficulty with this approach is the definition and measurement of individual utility functions or aggregate utility functions at a level where empirical estimation may be more feasible. There is also difficulty in specifying the nature of travel as a good competing for time and money expenditures. Obviously there are too many separate trips to see each one as a good so that some aggregate or abstract level of travel must be considered to remain within the bounds of computational limitations. Clearly what is suggested is aggregating individual travel behaviour as opposed to disaggregating group behaviour. For the time being, the latter seems more tractible.

CHAPTER III

CASE STUDY OF EMPLOYEES OF FORT GARRY INDUSTRIAL AREA NO. 1 - WINNIPEG

Objectives

In Chapter I, a number of factors and the manner in which they have been found to affect the separation of work and residence were discussed. In Chapter II, the application of some of these factors in the development of spatial interaction models was reviewed. The purpose of this Chapter is to apply and test some of the observations, hypotheses and models described in the literature to a situation in Winnipeg, Manitoba.

Obviously, it would be impossible to be as comprehensive as research to date and limitations of time, resources and data availability must be recognized. Consequently, a case study approach was adopted and a limited sample of workers surveyed to test a few of the more fundamental aspects of work-residence interaction. Specifically, the following questions were selected for investigation:

1) Is the worktrip travel time distribution similar to a gamma distribution, as suggested by Voorhees?

2) Is the opportunity travel time distribution similar to a normal distribution?

3) Is the worktrip per opportunity travel time distribution similar to a negative exponential distribution?

4) What impact does employer characteristics, such as type of business, previous location, year of established and proportion of employees by sex and occupation, have on average home/work separation?

5) Do males exhibit a greater average separation than females?

6) Do white-collar occupation groups exhibit a greater average separation than blue-collar groups?

7) Within the same time/distance interval, is there a greater proportion of workers residing on the same side of the Red and Assiniboine Rivers as their place of work than one would expect, given the distribution of residential opportunities?

8) Within the same time/distance interval, is there a greater proportion of workers residing on the suburban side of their place of work, as opposed to the central business district side than one would expect, given the distribution of residential opportunities?

9) Which of the following spatial interaction models duplicate the observed travel pattern:

   a) Entropy maximizing gravity model employing ${t_{i,j}}^{-x}$ as an impedance function;

   b) Entropy maximizing gravity model employing $e^{-\beta t_{i,j}}$ as an impedance function;

c) Tomazinis' competing opportunities model; or

d) Schneider's intervening opportunities model?

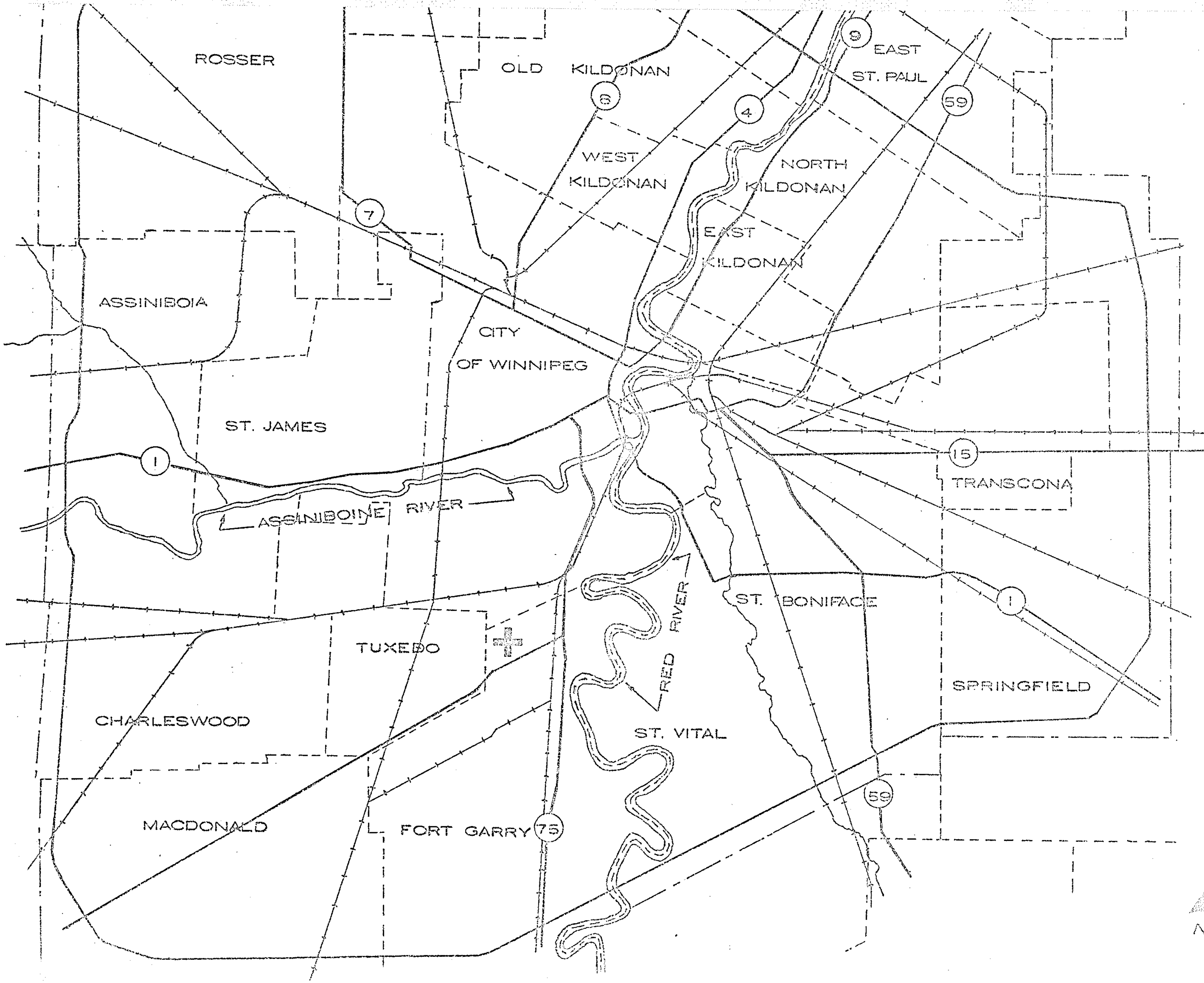
Method

The first step in conducting the case study was to gather a sample of data linking place of work to place of residence. Since this was not readily available, through the census or other sources at the time, data was gathered in the field.

Because it was clearly more efficient to obtain the data from a limited number of employers rather than from a large number of employee residences, a well-defined industrial area was selected for the survey. Besides the central employment district, Winnipeg has six such distinct areas; Fort Garry Industrial Park, Inkster Industrial Park, St. Boniface Industrial Area, St. James Industrial Area, Transcona Industrial Park and Tuxedo Industrial Park.

A portion of the Fort Garry Industrial Park, Area No. 1, was selected because it was relatively compact, was contained within a single census tract and traffic zone, and contained a variety of firms. Area No. 1 is located in the Fort Garry community north of McGillivray Boulevard and east of Waverly Street, as indicated on Map 1.

The firms to be sampled were chosen on the basis of the year they established in the area. The time frame, 1961 to 1971, was chosen because



MAP 1: LOCATION OF FORT GARRY INDUSTRIAL AREA NO. 1

of the availability of before and after census data. Also, since the survey was conducted in early 1974, this allowed a minimum period of about three years for employees to adjust their place of residence to that of their place of work. Of the fifteen firms, which established in the area during the sample period, only one declined to provide the information requested. Map No. 2 illustrates the layout of Area No. 1 and the names, locations and dates of the firms established there. It also identifies the firms which were surveyed.

A manager in each firm was interviewed and asked to provide the following information:

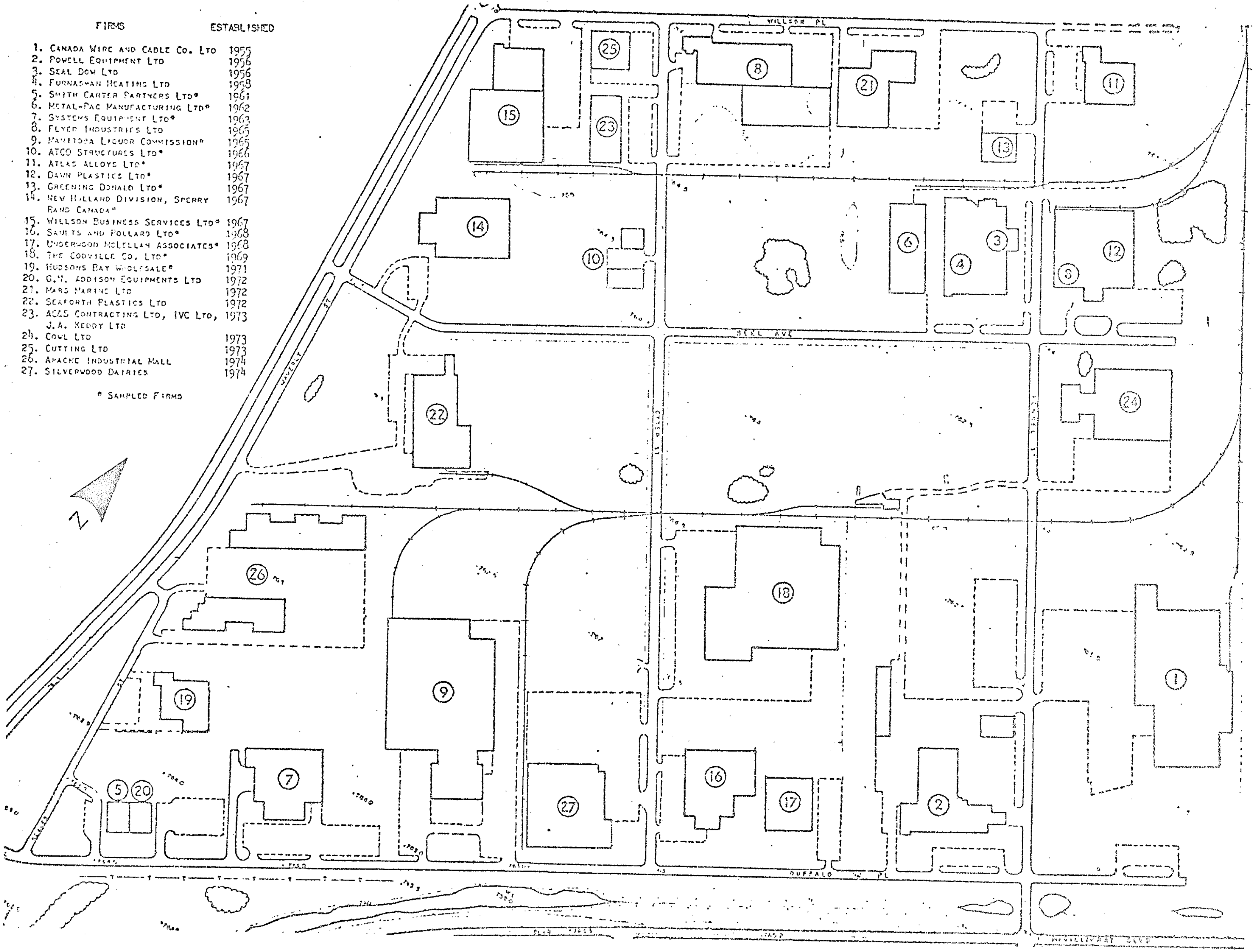
1) The name of the firm and type of business conducted there;
2) The date the firm located in the area, the reasons for locating there, and its previous location; and,
3) The number of employees, their residential address, sex and occupation.[1]

This resulted in a total sample of 778 employees from all fourteen firms. Subsequently, it was found that twenty-nine employees or approximately 3.7 percent had addresses which were rural or otherwise not

1 Some of the firms surveyed showed reluctance to release the exact addresses of their employees so the nearest "hundred block" address was obtained.

	FIRMS	ESTABLISHED
1.	CANADA WIRE AND CABLE CO. LTD	1955
2.	POWELL EQUIPMENT LTD	1956
3.	SEAL DOW LTD	1956
4.	FURNASMAN HEATING LTD	1958
5.	SMITH CARTER PARTNERS LTD*	1961
6.	METAL-PAC MANUFACTURING LTD*	1962
7.	SYSTEMS EQUIPMENT LTD*	1963
8.	FLYER INDUSTRIES LTD	1965
9.	MANITOBA LIQUOR COMMISSION*	1965
10.	ATCO STRUCTURES LTD*	1966
11.	ATLAS ALLOYS LTD*	1967
12.	DAWN PLASTICS LTD*	1967
13.	GREENING DONALD LTD*	1967
14.	NEW HOLLAND DIVISION, SPERRY RAND CANADA*	1967
15.	WILLSON BUSINESS SERVICES LTD*	1967
16.	SAULTS AND POLLARD LTD*	1968
17.	UNDERWOOD MCLELLAN ASSOCIATES*	1968
18.	THE CODVILLE CO. LTD*	1969
19.	HUDSONS BAY WHOLESALE*	1971
20.	G.N. ADDISON EQUIPMENTS LTD	1972
21.	MARS MARINE LTD	1972
22.	SEAFORTH PLASTICS LTD	1972
23.	AC&S CONTRACTING LTD, IVC LTD, J.A. KEDDY LTD	1973
24.	COWL LTD	1973
25.	CUTTING LTD	1973
26.	APACHE INDUSTRIAL MALL	1974
27.	SILVERWOOD DAIRIES	1974

* SAMPLED FIRMS



MAP 2: FIRMS LOCATED IN FORT GARRY INDUSTRIAL AREA NO. 1

traceable. These were deleted, leaving a sample of 749 employees or approximately 0.34 percent of the metropolitan work force. Table 1 shows the distribution of the final sample by employer, sex and occupation.

The next step was to determine the worktrip travel time separation for each employee sampled. In order to accomplish this, it was necessary to determine the automobile driving time from the centroid of all City traffic zones to that of zone 442, which corresponds with the location of Fort Garry Industrial, Area No. 1. Automobile zone to zone travel times characteristic of the Winnipeg street system during the 1971 A.M. peak hour were obtained from the Streets and Transportation Division of the civic administration.[1] 1962 travel time data from the Winnipeg Area Transportation Study was also employed to round out the 1971 data, which did not contain travel times from all zones, as indicated in Table 2. Relying primarily on 1971 information and knowledge of Winnipeg's arterial street system, a series of travel time isolines or contours at five minute intervals were plotted by hand on a city map.[2] The resulting travel time intervals are shown in relation to traffic zones on Map 3.

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1 It was assumed that all employees travelled by automobile since only one bus served Area No. 1 at the A.M. and P.M. peak. Managers stated this was not convenient for their employees and estimated that 95% or more arrived by car.

2 A SYMAP computer graphics program was initially employed to interpolate travel time isolines; however, it was not able to adequately account for speed differentials on major thoroughfares.

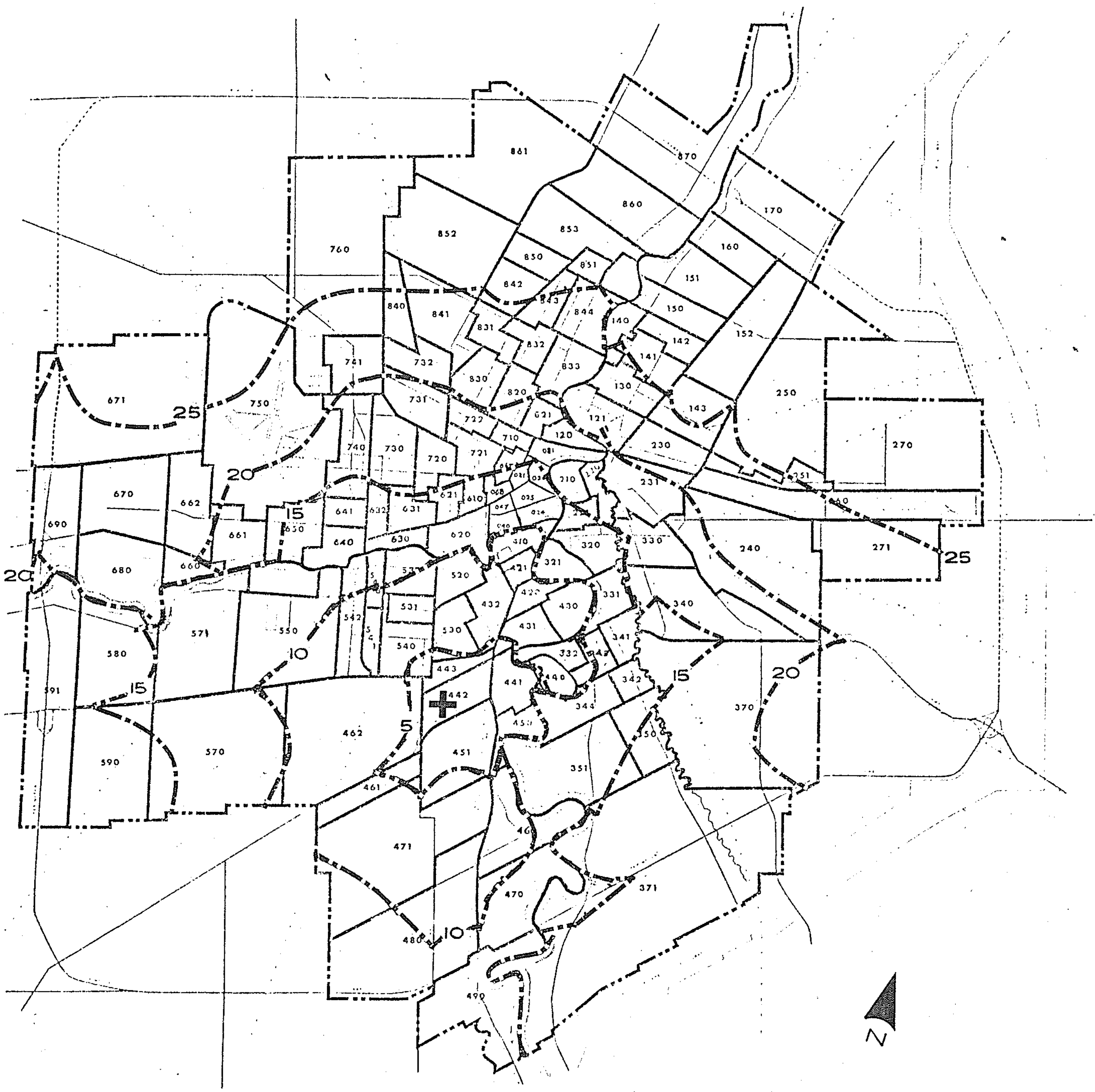
TABLE 1: FORT GARRY INDUSTRIAL AREA NO. 1 EMPLOYEE SAMPLE

Employer	Business	Year Est.	Previous Location	Employees Sampled	Males[1] Group A	Males Group B	Males Group C	Females Group A	Females Group B	Females Group C	Average Separation
Smith Carter Partners Ltd.	Architect	1961	Downtown	46 (100%)	38 (82.6%)	1 (2.2%)	0 (0.0%)	2 (4.3%)	5 (10.9%)	0 (0.0%)	13.5 minu
Metal Pac Mfg. Ltd.	Metal Products	1962	Fort Rouge	46 (100%)	3 (6.5%)	2 (4.3%)	39 (84.8%)	0 (0.0%)	2 (4.3%)	0 (0.0%)	11.3 minu
Systems Equip. Ltd.	Business Forms & Services	1963	Fort Rouge	120 (100%)	12 (10.0%)	16 (13.3%)	39 (32.5%)	0 (0.0%)	18 (15.0%)	35 (29.2%)	12.5 minu
Manitoba Liquor Comm.	Liquor Distr. & Control	1965	-	148 (100%)	28 (18.9%)	44 (29.7%)	44 (29.7%)	1 (0.7%)	30 (20.3%)	1 (0.7%)	14.4 minu
ATCO Struct. Ltd.	Building Modules	1966	new firm	11 (100%)	2 (18.2%)	4 (36.4%)	4 (36.4%)	0 (0.0%)	1 (9.1%)	0 (0.0%)	15.7 minu
Atlas Alloys Ltd.	Metal Products	1967	St. Boniface	19 (100%)	2 (10.5%)	8 (42.1%)	5 (26.3%)	0 (0.0%)	4 (21.1%)	0 (0.0%)	15.7 minu
Dawn Plastics Ltd.	Plastic Products	1967	St. James	10 (100%)	2 (20.0%)	0 (0.0%)	7 (70.0%)	0 (0.0%)	1 (10.0%)	0 (0.0%)	12.5 minu
Greening Donald Ltd.	Metal Products	1967	St. James	4 (100%)	1 (25.0%)	2 (50.0%)	1 (25.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	22.5 minu
New Holland Div. Sperry Rand Canada	Farm Equipment	1967	St. James	19 (100%)	4 (21.1%)	7 (38.8%)	2 (10.5%)	0 (0.0%)	6 (31.6%)	0 (0.0%)	17.2 minu
Willson Bus. Services Ltd.	Business Forms & Services	1967	Downtown	97 (100%)	16 (16.5%)	22 (22.2%)	10 (10.3%)	1 (1.0%)	48 (49.5%)	0 (0.0%)	13.5 minu
Saults and Pollard Ltd.	Printing	1968	Downtown	49 (100%)	5 (10.2%)	4 (8.2%)	28 (57.2%)	0 (0.0%)	4 (8.2%)	8 (16.3%)	14.5 minu
Underwood McLellan Ass.	Engineers Planners	1968	Ft. Garry	79 (100%)	62 (78.5%)	5 (6.3%)	2 (2.5%)	0 (0.0%)	10 (12.7%)	0 (0.0%)	13.2 minu
The Codville Co. Ltd.	Wholesale Grocers	1969	St. James	58 (100%)	18 (31.0%)	5 (8.6%)	21 (36.2%)	0 (0.0%)	14 (24.1%)	0 (0.0%)	17.2 minu
Hudson's Bay Wholesale	Wholesale Distr.	1971	Downtown	43 (100%)	1 (2.3%)	8 (18.6%)	23 (53.5%)	0 (0.0%)	7 (16.3%)	4 (9.3%)	13.7 minu
TOTAL SAMPLE				749 (100%)	144 (25.9%)	128 (17.1%)	225 (30.0%)	4 (0.6%)	150 (20.0%)	48 (6.4%)	13.9 minu

1 Note: Occupation groups A, B, and C are defined in Table 4.

Table 2: A.M. Peak-Hour Automobile Travel Times from Zone 442 to all Other Zones

Centroid No.	Zone No.	1962 Min.	1971 Min.	Centroid No.	Zone No.	1962 Min.	1971 Min.	Centroid No.	Zone No.	1962 Min.	1971 Min.	Centroid No.	Zone No.	1962 Min.	1971 Min.
001	020	15	-	032	271	25	-	063	471	09	6.1	094	680	22	24.1
002	021	15	-	033	320	13	-	064	480	11	5.7	095	690	20	-
003	024	12	10.8	034	321	14	-	065	490	15	-	096	710	18	-
004	025	13	-	035	330	18	-	066	520	09	-	097	720	18	17.5
005	046	12	9.4	036	331	12	10.5	067	530	07	6.4	098	721	17	16.2
006	047	13	-	037	332	10	-	068	531	08	-	099	722	19	-
007	067	16	13.3	038	340	16	15.7	069	532	09	12.7	100	730	19	-
008	068	14	-	039	341	13	10.8	070	540	06	-	101	731	20	-
009	081	17	-	040	342	14	12.1	071	541	08	-	102	732	24	-
010	120	19	-	041	343	12	9.0	072	542	09	-	103	740	17	-
011	121	22	21.1	042	344	12	10.1	073	543	10	10.3	104	741	23	-
012	130	23	-	043	350	16	15.0	074	550	12	-	105	750	19	-
013	140	25	26.9	044	351	15	13.1	075	570	10	-	106	760	24	-
014	141	25	28.3	045	370	15	-	076	571	14	11.8	107	820	21	-
015	142	27	-	046	371	19	-	077	580	20	15.9	108	821	19	-
016	143	24	25.6	047	410	11	9.6	078	590	14	-	109	830	22	22.8
017	150	28	28.4	048	420	09	7.9	079	591	18	-	110	831	24	24.3
018	151	28	-	049	421	10	8.5	080	610	13	-	111	832	22	-
019	152	25	-	050	430	09	8.1	081	620	12	12.4	112	833	21	21.8
020	160	31	-	051	431	08	-	082	621	15	14.0	113	840	25	-
021	170	30	-	052	432	08	8.0	083	630	15	12.8	114	841	25	23.4
022	210	17	-	053	440	07	-	084	631	15	11.6	115	842	26	26.3
023	220	16	-	054	441	04	4.3	085	632	15	-	116	843	25	22.7
024	221	16	-	055	442	00	-	086	640	14	11.4	117	844	24	24.7
025	230	22	23.3	056	443	06	4.9	087	641	14	12.9	118	850	29	-
026	231	18	-	057	450	06	3.7	088	650	15	13.6	119	851	26	-
027	240	19	-	058	451	06	-	089	660	23	-	120	852	27	-
028	250	27	-	059	460	09	-	090	661	20	15.4	121	853	29	-
029	251	23	-	060	461	07	-	091	662	21	24.8	122	860	28	-
030	260	25	-	061	462	08	-	092	670	22	23.8	123	861	30	-
031	270	28	27.8	062	470	12	10.8	093	671	28	-	124	870	29	-



MAP 3. FIVE MINUTE TRAVEL TIME ISOLINES FROM FORT GARRY INDUSTRIAL AREA NO.1 TO WINNIPEG TRAFFIC ZONES

Having determined the extent of five minute travel time intervals over the entire urban area, 1971 census tracts were allocated to their respective interval. The pattern of census tracts and the approximate extent of residential development contained in each are illustrated on Map 4. Map 3 was then superimposed on Map 4 and each census tract was assigned a travel time interval according to the location of the geometric centroid of the residentially-developed portion of the tract. The resulting allocation is presented in Table 3.

Next each employee was assigned by sex and occupation group to a census tract and hence to a travel time interval. The sample was divided into three major occupation groups for each sex, as indicated in Table 4, and each employee was classified according to the sex and occupation specified by his employer.[1]

The residence of each employee was then located in a census tract according to the address provided.[2] Using Table 3, the employee sample was grouped according to travel-time interval of residence, as well as sex and occupation.

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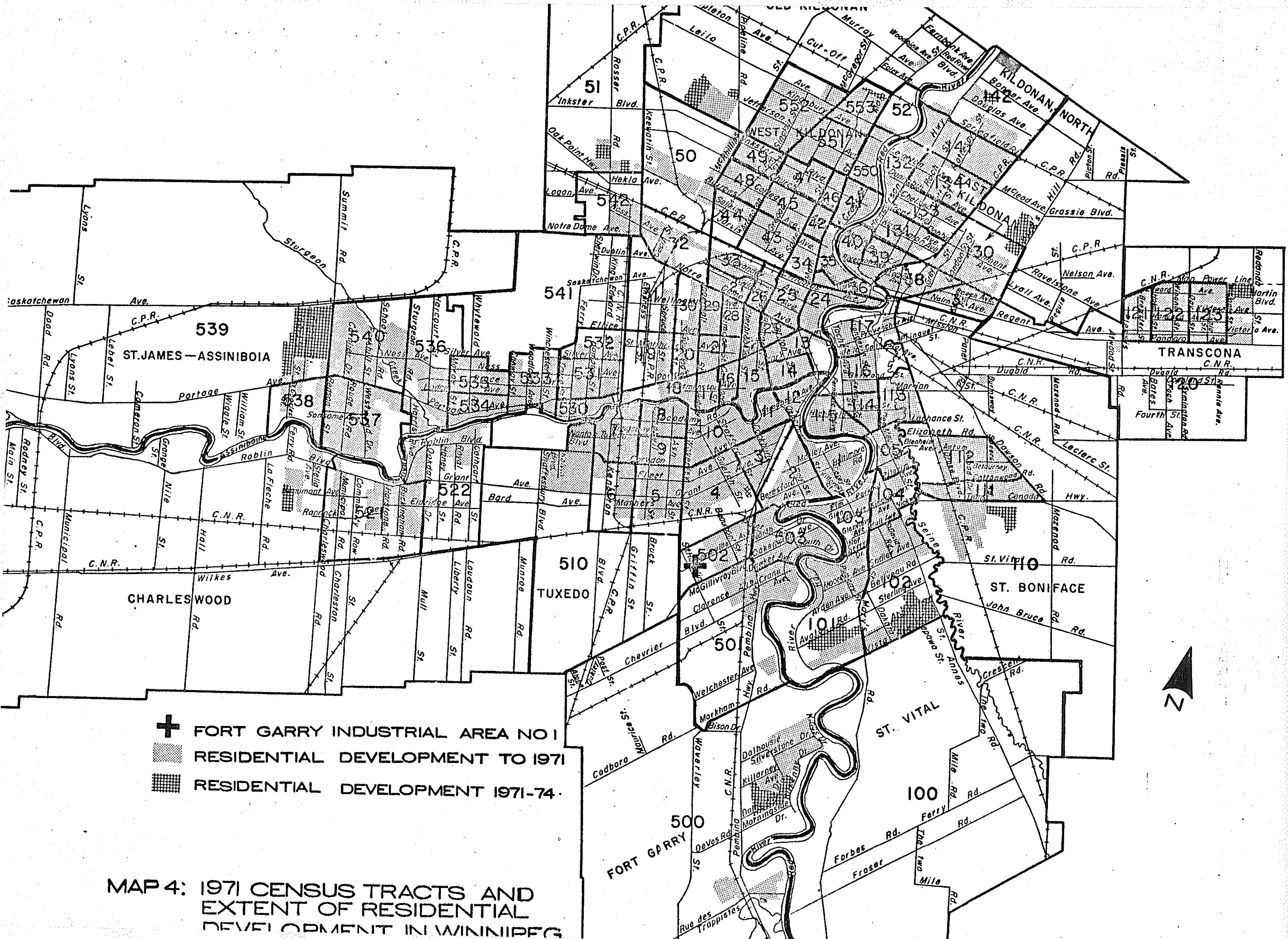
1 This process was facilitated by use of the "Occupational Classification Manual, Census of Canada, 1971", Volume 1, Catalogue No. 12-536.

2 This was accomplished using the "Winnipeg Street, Index, Census of Canada, 1971". Where only the nearest "hundred block" address was provided, it was sometimes possible to assign any of two or three census tracts. In these cases, it was assigned to the tract containing the greatest number of potentially-suitable addresses. Some streets and addresses were not contained in the 1971 index because they had not yet been developed. These were assigned to the appropriate tract using a commercially-available map and index for 1974.



MAP 4: 1971 CENSUS TRACTS AND EXTENT OF RESIDENTIAL DEVELOPMENT IN WINNIPEG

Table 3: Allocation of 1971 Winnipeg Census Tracts to 5-Minute Travel Time Intervals from Fort Garry Industrial Area No. 1

Travel Time Interval	Census Tracts
0-5 minutes	501, 502, 503.
5-10 minutes	1, 2, 3, 4, 5, 6, 9, 10, 11, 12, 103.
10-15 minutes	7, 8, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 101, 102, 104, 105, 110, 111, 113, 114, 115, 116, 500, 510, 522, 530, 531, 532, 533.
15-20 minutes	24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 100, 112, 117, 520, 521, 534, 535, 541, 542.
20-25 minutes	37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 131, 536, 537, 538, 539, 540, 550, 551.
25-30 minutes	52, 120, 121, 122, 123, 130, 132, 133, 134, 140, 141, 142, 552, 553, other parts of Old Kildonan.

Table 4: Composition of Occupational Groups

Group A	Census Group 11	Municipal, Administration and Related Occupations
	27	Teaching and Related Occupations
	31	Occupations in Medicine and Health
	21	Occupations in Natural Sciences, Engineering and Mathematics
	23	Occupations in Social Sciences and Related Fields
	25	Occupations in Religion
	33	Artistic, Literary and Related Occupations
Group B	Census Group 41	Clerical and Related Occupations
	51	Sales Occupations
Group C	Census Group 61	Service Occupations
	81/82	Processing Occupations
	83	Machinery and Related Occupations
	85	Product Fabricating, Assembling and Repairing Occupations
	87	Construction Trades Occupations
	91	Transport Equipment Operating Occupations
	other	Materials Handling and Related Occupations, Other Crafts and Equipment Operating Occupations and Occupations Not Elsewhere Classified.

Note: Census Groups 71, 73, 75 and 77 covering primary occupations such as Fishing, Farming, Logging and Mining were not included because they were not included in the employee sample and were not considered representative of occupations in an urban industrial park.

Percentages in each time interval and average work-residence separation were calculated for each sex and occupation group, as presented in Table 5.

Average travel-time separation was computed by assuming a travel time equal to the midpoint of each interval for every employee residing in that interval. For example, a travel time of 12.5 minutes was assumed for all employees in the ten to fifteen minute interval.

The worker population, residing in each travel time interval, was assumed to be a suitable indicator of the number of residential opportunities available there. Accordingly, the working population in each sex and occupation category was obtained from 1971 census tract information and assigned to a time interval using Table 3.[1] Percentages in each time interval and average opportunity separation were then calculated for each group, as shown in Table 6.

Next, the number of Area No. 1 employees actually residing in each time interval as a proportion of the opportunities available there was computed. The number of employees in each time interval and category was divided by number of workers, in thousands, residing in the same interval and belonging to the same category. These figures were then normalized; such that, the total in each sex and occupation group was one

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1 Statistics Canada, "Winnipeg, Population and Housing Characteristics by Census Tracts, 1971 Census of Canada", Series B, Catalogue 95-753 (CT-22B, July 1975) pp. 14-25.

Table 5: Worktrip Travel Time Distribution for Employee Sample

	No. of Employees Residing in Travel Time Interval							
	0-5 Min.	5-10 Min.	10-15 Min.	15-20 Min.	20-25 Min.	25-30 Min.	Total 0-30 Min.	Average Travel Time Min.
Males								
Group A	17 (8.8%)	39 (20.1%)	58 (29.9%)	24 (12.4%)	39 (20.1%)	17 (8.7%)	194 (100%)	14.6
Group B	13 (10.2%)	22 (17.2%)	42 (32.8%)	14 (10.9%)	20 (15.6%)	17 (13.3%)	128 (100%)	14.7
Group C	22 (9.8%)	40 (17.8%)	71 (31.6%)	28 (12.4%)	38 (16.9%)	26 (11.5%)	225 (100%)	14.7
Total	52 (9.5%)	101 (18.5%)	171 (31.2%)	66 (12.1%)	97 (17.7%)	60 (11.0%)	547 (100%)	14.6
Females								
Group A	0 (0.0%)	1 (25.0%)	2 (50.0%)	0 (0.0%)	1 (25.0%)	0 (0.0%)	4 (100%)	13.8
Group B	26 (17.3%)	34 (22.7%)	55 (36.6%)	16 (10.7%)	13 (8.7%)	6 (4.0%)	150 (100%)	11.6
Group C	6 (12.5%)	14 (29.2%)	15 (31.3%)	4 (8.3%)	5 (10.4%)	4 (8.3%)	48 (100%)	12.5
Total	32 (15.8%)	49 (24.3%)	72 (35.6%)	20 (9.9%)	19 (9.4%)	10 (5.0%)	202 (100%)	11.9
Total Sample	84 (11.2%)	150 (20.0%)	243 (32.4%)	86 (11.5%)	116 (15.5%)	70 (9.4%)	749 (100%)	13.9

Note: The figure in brackets is the percentage of the employee sample in each travel time interval for each age and occupation category.

Table 6: Travel Time Distribution of Residential Opportunities (Winnipeg's Worker Population) Around Industrial Area No. 1

	Travel Time Interval Working Population 0-5 Min.	5-10 Min.	10-15 Min.	15-20 Min.	20-25 Min.	25-30 Min.	Total 0-30 Min.	Average Opportunity Separation Min.
Males								
Group A	1,455 (5.2%)	5,540 (19.8%)	8,760 (31.3%)	2,865 (10.2%)	5,505 (19.6%)	3,905 (13.9%)	28,030 (100%)	15.5
Group B	1,135 (3.4%)	5,020 (15.1%)	9,550 (28.8%)	4,400 (13.3%)	7,535 (22.7%)	5,530 (16.7%)	33,170 (100%)	16.8
Group C	1,825 (2.4%)	7,545 (10.0%)	21,935 (29.0%)	13,310 (17.6%)	18,965 (25.1%)	12,005 (15.9%)	75,585 (100%)	17.5
Total	4,415 (3.2%)	18,105 (13.2%)	40,245 (29.4%)	20,575 (15.1%)	32,005 (23.4%)	21,440 (15.7%)	136,785 (100%)	17.0
Females								
Group A	605 (3.4%)	3,555 (20.1%)	6,070 (34.3%)	2,500 (14.1%)	3,010 (17.0%)	1,970 (11.1%)	17,710 (100%)	15.2
Group B	1,245 (2.9%)	6,520 (15.4%)	13,490 (31.8%)	5,535 (13.0%)	9,060 (21.4%)	6,565 (15.5%)	92,415 (100%)	16.5
Group C	485 (2.0%)	2,435 (10.0%)	7,480 (30.6%)	4,855 (19.9%)	6,370 (26.1%)	2,785 (11.4%)	24,410 (100%)	17.1
Total	2,335 (2.8%)	12,510 (14.8%)	27,040 (32.0%)	12,890 (15.2%)	18,440 (21.8%)	11,320 (13.4%)	84,535 (100%)	16.4
Total Sample	6,750 (3.1%)	30,615 (13.8%)	67,285 (30.4%)	33,465 (15.1%)	50,445 (22.8%)	32,760 (14.8%)	221,320 (100%)	16.8

Note: The figure in brackets is the percentage of resident workers in each travel time interval for each age and occupation category.

hundred in order that effective comparisons could be made between groups. The result can also be interpreted as a measure of the relative frequency of travel propensities for each group, since the effect of its particular opportunity distribution has been eliminated. This information and the average travel propensity for each group is presented in Table 7.

The distribution of sample employees with respect to possible psychological travel barriers imposed by the Red and Assiniboine Rivers and the inner-city area was also investigated. The second, third and fourth travel-time intervals contain census tracts on the same side of the two rivers as Area No. 1 as well as on the opposite sides. Within the same intervals, the number of employees, per thousand residential opportunities on either side, were compared; as shown in Table 8.

In determining the impact of the inner-city area on the directional distribution of worktrips to Industrial Area No. 1, it was necessary to distinguish between those census tracts located on the suburban side of the place of work, as opposed to those located on the inner-city side. This was accomplished by drawing a straight line between the centroid of Area No. 1, that is census tract 502 and the corner of Portage Avenue and Main Street. The inner city was assumed to subtend an angle of ninety degrees centered on this line. By projecting the sides of the angle, it was possible to delimit suburban census tracts from inner-city tracts. Then, within the same travel-time intervals, the number of employees per thousand residential opportunities located on the suburban side was compared with the inner-city side and presented in Table 9.

Table 7: Travel Time Distribution of Employee Residences per 1,000 Residential Opportunities

	No. of Employees per 1,000 Workers Residing in Travel Time Interval							
	0-5 Min.	5-10 Min.	10-15 Min.	15-20 Min.	20-25 Min.	25-30 Min.	Total	Average Travel Propensity Min.
Males								
Group A	11.7 (25.9)	7.0 (15.6)	6.6 (14.7)	8.4 (18.4)	7.1 (15.7)	4.4 (9.6)	45.2 (100)	13.1
Group B	11.5 (39.3)	4.4 (15.0)	4.4 (15.1)	3.2 (10.9)	2.7 (9.1)	3.1 (10.6)	29.1 (100)	10.9
Group C	12.1 (44.9)	5.3 (19.7)	3.2 (12.0)	2.1 (7.8)	2.0 (7.5)	2.2 (8.1)	26.9 (100)	9.4
Total	11.8	5.6	4.2	3.2	3.0	2.8	30.6	10.6
Females								
Group A	0.0 (0.0)	0.3 (29.8)	0.3 (34.9)	0.0 (0.0)	0.3 (35.2)	0.0 (0.0)	0.9 (100)	14.2
Group B	20.9 (59.0)	5.2 (14.7)	4.1 (11.5)	2.9 (8.2)	1.4 (4.0)	0.9 (2.6)	35.4 (100)	7.1
Group C	12.4 (53.4)	5.7 (24.8)	2.0 (8.7)	0.8 (3.5)	0.8 (3.4)	1.4 (6.2)	23.2 (100)	7.3
Total	13.7 (57.7)	3.9 (16.5)	2.7 (11.2)	1.6 (6.5)	1.0 (4.3)	0.9 (3.7)	23.7 (100)	7.2
Total Sample	12.4 (44.5)	4.9 (17.5)	3.6 (12.9)	2.6 (9.2)	2.3 (8.2)	2.1 (7.7)	28.0 (100)	9.6

Note: The figure in brackets is resident employees sampled per 1,000 resident workers <u>normalized</u> to total 100 for each sex and occupation category.

Table 8: Distribution of Employee Residences per 1,000 Residential Opportunities on the Industrial Area No. 1 Side and Opposite Sides of the Red and Assiniboine Rivers

Travel Time Interval	Industrial Area No. 1 Side				Opposite Side				Both Sides		
	Census Tracts	Employees	Opportunities	Employee per 1,000 Opportunities	Census Tracts	Employees	Opportunities	Employee per 1,000 Opportunities	Employees	Opportunities	Employee per 1,000 Opportunities
5-10 Min.	1,2,3,4,5, 6,9,10,11, 12	139	28,815	4.8	103	11	1,800	6.1	150	30,615	4.9
10-15 Min.	7,8,500, 510,522	70	10,565	6.6	13,14,15, 16,17,18, 19,20,21, 22,23,101, 102,104,105, 110,111,113, 114,115,116, 530,531,532, 533	173	56,720	3.1	243	67,285	3.6
15-20	520,521	20	3,025	6.6	24,25,26, 27,28,29, 30,31,32, 33,34,35, 36,100,112, 117,534,535, 541,542	66	30,440	2.2	86	33,465	2.6

Table 9: Distribution of Employee Residences per 1,000 Residential Opportunities on the Suburban and Inner-City Side of Industrial Area No. 1

Travel Time Interval	Suburban Side Census Tracts	Suburban Side Employees	Suburban Side Opportunities	Suburban Side Employees per 1,000 Opportunities	Inner-City Side Census Tracts	Inner-City Side Employees	Inner-City Side Opportunities	Inner-City Side Employees per 1,000 Opportunities	Both Sides Employees	Both Sides Opportunities	Both Sides Employees per 1,000 Opportunities
5-10 Min.	5,6,103	23	6,135	3.7	1,2,3,4, 9,10,11,12	127	24,480	5.2	150	30,615	4.9
10-15 Min.	7,101,102 104,110,111, 500,510,522, 530,531,532, 533	166	31,090	5.3	8,13,14,15 18,19,20,21, 22,23,105, 113,114,115 116	77	36,195	2.1	243	67,285	3.6
15-20 Min.	100,112,520, 521,534,535	52	11,360	4.6	24,25,26,27, 28,29,30,31, 32,33,34,35, 36,117,541, 542	34	22,105	1.5	86	33,465	2.6
20-25 Min.	536,537,538, 539,540	46	14,115	3.3	37,38,39,40, 41,42,43,44, 45,46,47,48, 49,50,51,131, 550,551	53	36,330	1.5	99	50,445	2.0

Lastly, theoretical worktrip travel-time distributions were produced using four different spatial interaction models. These were compared with the distribution actually observed for Area No. 1 employees.

Using a common notation, the equations employed to calculate the four theoretical distributions are, as follows:

1. Gravity Model ($F_{i,j} = t_{i,j}^{-x}$)

$$V_{i,j} = \frac{V_j \, W_i \, t_{i,j}^{-x}}{\sum_{i=1}^{6} W_i \, t_{i,j}^{-x}}$$

2. Gravity Model ($F_{i,j} = e^{-\beta t_{i,j}}$)

$$V_{i,j} = \frac{V_j \, W_i \, e^{-\beta t_{i,j}}}{\sum_{i=1}^{6} W_i \, e^{-\beta t_{i,j}}}$$

3. Schneider's Intervening Opportunities Model

$$V_{i,j} = \frac{V_j \left[e^{-LW} - e^{-L(W+W_i)}\right]}{\sum_{i=1}^{6} \left[e^{-LW} - e^{-L(W+W_i)}\right]}$$

4. Tomazinis Competing Opportunities Model

$$V_{i,j} = \frac{V_j \left[\dfrac{W_i}{W+W_i}\right] \left[\dfrac{W_i}{\sum_{i=1}^{6} W_i}\right]}{\sum_{i=1}^{6} \left[\dfrac{W_i}{W+W_i}\right] \left[\dfrac{W_i}{\sum_{i=1}^{6} W_i}\right]}$$

Where $V_{i,j}$ is the volume of trips from origin time interval, i, to the destination, Area No. 1 or rather the number of employees of Area No. 1 residing in time interval i;

V_j is the total number of employee worktrip destinations in Area No. 1;

W_i is an index of worktrip emissivity or the number of workers residing in interval i;

W is the total number of workers residing in intervals up to, but not including, interval i, or the total number of residential opportunities between Area No. 1 and interval i;

$t_{i,j}$ is the travel time from the midpoint of origin interval i to the destination, Area No. 1; and

x, β and L are model parameters determined by calibrating the theoretical distributions with respect to the observed distribution.

A number of modifications to the models discussed in Chapter II are evident in the equations presented above. Firstly, since the total number of worktrips originating in any given origin interval is not known, only destinations at Area No. 1 are constrained exogenously. This means that these equations actually represent residential location models as opposed to trip-distribution models.

Secondly, Schneider's Opportunity Model normally deals with an unbounded region. In order to facilitate comparison with the other three models on the basis of a closed system, it was necessary to normalize the probability of a trip originating in interval i, such that the probabilities totaled unity for the six intervals under discussion.

Finally, Tomazinis' Opportunity Model was modified by proposing a new "probability of satisfaction". Close examination of Tomazinis' formula will reveal the fact that the number of trips predicted as originating in the interval closest to the destination will always be greater than the number predicted for any other interval.

This is clearly contrary to Voorhees' observation, cited earlier, that worktrip distributions generally approximate a gamma distribution. Consequently, the ratio of trip-end opportunities in interval i to the total opportunities in the region was employed as an alternative to the ratio of opportúnities outside of interval i to the total in the region. This new probability of satisfaction is at least as logical as Tomazinis' and results in a distribution more representative of actual tripmaking behaviour.

All of the models with the exception of Tomazinis' require calibration and the estimation of empirical parameters. For the first trial of the Gravity Model with $T_{i,j}^{-x}$ as an impedance factor, x was set at unity, and for the first trial with $e^{-\beta t_{i,j}}$ as an impedance factor, β was assumed to be the inverse of the average trip-end opportunity spacing given in Table 6. The initial value for L in Schneider's Intervening Opportunity Model was estimated from the slope of the line defined by the equation:

$$-LW = \ln (1 - P(W))$$

where W is the number of intervening opportunities up to the interval being considered; and

P(W) is the ratio of intervening opportunities to the total in the region.

Next a chi-square goodness of fit test was applied. The parameter values for each model requiring calibration were then adjusted by trial and error within two significant figures until the value of χ^2 was minimized.[1]

As a null hypothesis, it was assumed that there was no difference between the observed frequencies and the theoretical frequencies derived from the models. Since there are six travel time intervals, there are five degrees of freedom for the expected distribution produced by Tomazinis' Model and four for the other models, which each employ a parameter calibrated from the sample distribution. At a level of significance of 0.01, the critical values[2] for χ^2 are:

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1 The chi-square statistic is defined to be $\chi^2 = \sum_{i=i}^{n} \frac{(f_i - e_i)^2}{e_i}$
were f_i is the observed frequency in interval i and e_i is the theoretical expected frequency in interval i. It can be applied to test the hypothesis that any given observed frequency distribution was selected from a universe having any specified type of multinomial distribution; provided that the total number of observations is large and each e_i is at least 5.

2 These values are available from chi-square tables in any basic statistics text.

$$\chi^2_{5,0.01} = 15.086$$

and

$$\chi^2_{4,0.01} = 13.277$$

for Tomazinis' Model and the other three models respectively.

If computed values of χ^2 exceeded these critical values, the null hypothesis was rejected on the grounds there is only a one percent probability that this would happen due to chance alone; assuming that the hypothesis was true. The alternate hypothesis, that there is a significant difference between observed and theoretical frequency distributions, was then accepted.

A Kolmogorov-Smirnov goodness of fit test was also applied in order to confirm the results given by chi-square.[1]

Each model was tested on four groups of employees:

1) males in professional and technical occupations (Group A);
2) males in blue-collar occupations (Group C);
3) females in clerical and sales occupations (Group B); and,
4) the total sample.

These groups were selected because of their sample size and the representative nature of their distribution. The travel time distributions

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1 The Kolmogorov-Smirnov test statistic is defined to be $K = D\sqrt{n}$ Where D is the largest absolute difference between the observed cumulative frequency proportion and the expected cumulative frequency proportion in any interval, and n is the sample size.

Table 10: Predicted Travel Time Distribution of Employee Residences for Four Spatial Interaction Models

Sex and Occupation Group	Interaction Model Employed	Employees Residing in Time Interval 0-5 Min.	5-10 Min.	10-15 Min.	15-20 Min.	20-25 Min.	25-35 Min.	Total	Parameter Value	Chi-Square Test χ^2	K.S. Test K
Males	Observed	17	39	58	24	39	17	194			
Group A	Gravity ($t_{i,j}^{-x}$)	15	44	61	19	33	22	194	x=0.25	4.525	0.432
	Gravity ($e^{-\beta t_{i,j}}$)	13	44	64	19	33	21	194	β=0.020	5.530	0.501
	Opportunity (Schneider's)	13	45	63	19	33	21	194	L=1.8×10^{-5}	51596	0.501
	Opportunity (Tomazinis')	22	66	73	6	19	8	194		100.442	3.371
Males	Observed	22	40	71	28	38	26	225			
Group C	Gravity ($t_{i,j}^{-x}$)	22	38	72	33	39	21	225	x=0.82	2.093	0.345
	Gravity ($e^{-\beta t_{i,j}}$)	13	38	82	36	38	18	225	β=0.062	13.145	0.735
	Opportunity (Schneider's)	11	39	85	36	37	17	225	L=2.0×10^{-5}	19.901	0.810
	Opportunity (Tomazinis')	12	39	99	26	37	12	225		32.792	1.140

Table 10: Predicted Travel Time Distribution of Employee Residences for Four Spatial Interaction Models

Sex and Occupation Group	Interaction Model Employed	Employees Residing in Time Interval 0-5 Min.	5-10 Min.	10-15 Min.	15-20 Min.	20-25 Min.	25-35 Min.	Total	Parameter Value	Chi-Square Test χ^2	K.S. Test K
Females	Observed	26	34	55	16	13	6	150			
Group B	Gravity ($t_{i,j}^{-x}$)	27	40	56	13	15	9	150	x=1.16	4.657	0.576
	Gravity ($e^{-\beta t_{i,j}}$)	16	47	56	13	13	5	150	β=0.110	10.756	0.808
	Opportunity (Schneider's)	13	52	56	12	12	5	150	L=6.6x10^{-5}	20.865	1.053
	Opportunity (Tomazinis')	9	42	65	9	17	8	150		42.059	1.384
Total	Observed	84	150	243	86	116	70	749			
Sample	Gravity ($t_{i,j}^{-x}$)	77	157	239	93	117	66	749	x=0.72	1.793	0.246
	Gravity ($e^{-\beta t_{i,j}}$)	52	170	271	98	107	51	749	β=0.064	34.243	1.177
	Opportunity (Schneider's)	44	175	275	95	108	52	749	L=0.7x10^{-5}	51.335	1.450
	Opportunity (Tomazinis')	50	185	319	60	99	36	749		94.155	2.819

Note: For Tomazinis' Model, there are five degrees of freedom and for a level of significance of 0.01, the critical value of χ^2 is 15.086. For the others, $\chi^2_{4,0.01}$ =13.277. In the Kolomogorov-Smirnov test, the critical value of K at a level of significance of 0.01 is 1.63.

predicted for each by the four different models are compared in Table 10.

Observations and Analysis

Frequency polygons for the worktrip travel time distribution of Area No. 1 employees and residential opportunities throughout Winnipeg are compared in Figure 8. Making allowances for the limited number of data points provided, it is quite clear that the shape of the observed employee worktrip distribution does resemble a gamma type distribution and the opportunity distribution is roughly similar to a normal distribution. A major distortion is evident in the fifteen to twenty minute travel time interval, which is due to the unusually low number of residential opportunities available there. Maps 3 and 4 indicate that the majority of land in the fifteen to twenty interval is either undeveloped or developed industrially. Given a more even distribution of residential opportunities throughout the City, the observed distributions would probably be very similar to the theoretical curves. Figure 8 also illustrates the distribution of worktrips per thousand opportunities normalized, and it is seen to exhibit a negative exponential-like decline with increasing travel time, as suggested in Chapter I.

The average automobile travel time for employees of Area No. 1, indicated in Table 5, which is in the order of thirteen to fifteen minutes, is representative of average automobile-commuting times for the city as a whole, as reported in recent surveys conducted by Statistics Canada.[1]

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1 Hanlon, "Travel to Work Survey", p. 9.

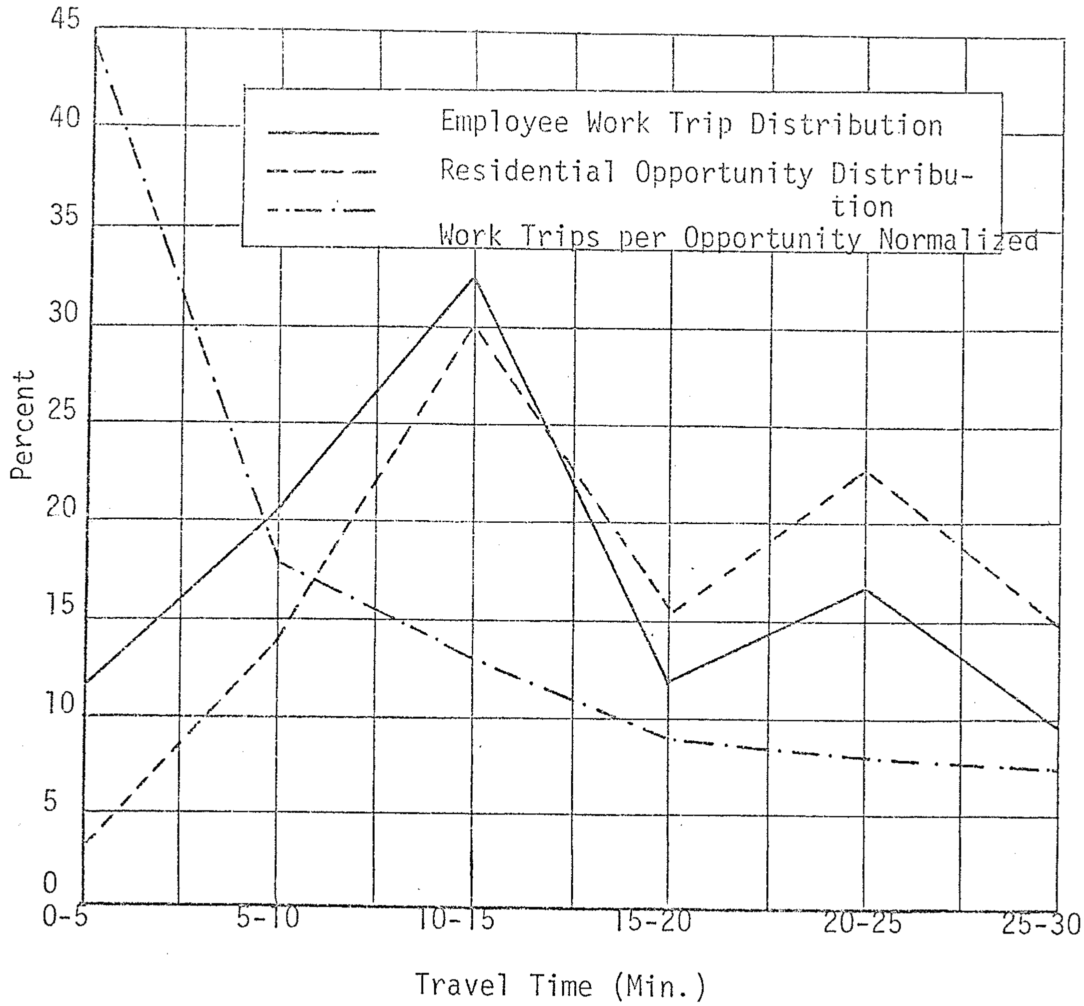

Figure 8: Work Trip Travel Time Distribution for Employees of Fort Garry Industrial Area No. 1 Compared With the Distribution of Residential Opportunities (Working Population) in Winnipeg.

The average travel time for the total employee sample is 13.9 minutes. Meanwhile, the average opportunity separation of worker residences for Area No. 1 is 16.8 minutes, indicating that workers there, as elsewhere, do attempt to reduce their journey to work.

Average work-residence separation for Area No. 1 employees varies from 11.3 minutes to 17.2 minutes according to their employer.[1] The majority of firms sampled relocated to Area No. 1 from some other location within the City; usually in order to obtain land for expansion at a reasonable price. It is clear, from the data presented in Table 1, that employees of those firms whose old locations were close to Area No. 1, have lower average worktrip travel times than employees of those firms new to the City or those whose old locations were further away from Area No. 1.

The date that each company located in Area No. 1 is also important. Firms, which have been in the area longer, have employees who live closer than those of more recently-established firms. Obviously, the adjustment of residential location to a new place of work continues over a fairly-long period; in this case, it is in the order of a decade.

The type of business conducted by a firm, in terms of the kind of employees it is likely to hire, also has a bearing on the average work-residence separation of its staff. Those firms with high proportions of

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1 The average travel time for Greening Donald Ltd. employees was 22.5 minutes; however, this represents only four workers and was not considered to be representative.

female or blue-collar workers exhibit a closer distribution of employee residences than those with a preponderance of male or white-collar workers.

As suggested in the literature, females were found to have a tighter distribution about their place of work than males. The average separation for female employees of Area No. 1 was 11.9 minutes; whereas, for males, it was 14.6 minutes. This is not merely a reflection of differences in average residential opportunity spacing for the two sexes, which were reasonably similar at 16.4 and 17.0 minutes respectively. The normalized distribution of employee residences, per thousand residential opportunities for the two sexes, are compared in Figure 9. The distribution for males is much flatter indicating their greater propensity for worktrip travel.[1]

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1 If one assumes the samples of men and women described here were drawn randomly from hypothetical populations for each sex, a test of statistical significance based on the standard error of the difference of their means may be constructed. At a 99% level of confidence, the difference of the means should not exceed 2.58 standard errors, if the population distributions are identical. The difference computed, however, is 5.57 standard errors so the null hypothesis is rejected and the average travel propensity for men and women can be assumed to be statistically significantly different. Owing to the actual sampling method used, however, it is not clear whether the sample distribution meets the criteria for the application of such parameteric tests. The result is nonetheless consistent with the application of the nonparametric Kolmogorov-Smirnov two sample test. At a 99% degree of confidence, the statistic K should not exceed a value of 1.63, whereas the value calculated is 2.34 and the null hypothesis is again rejected.

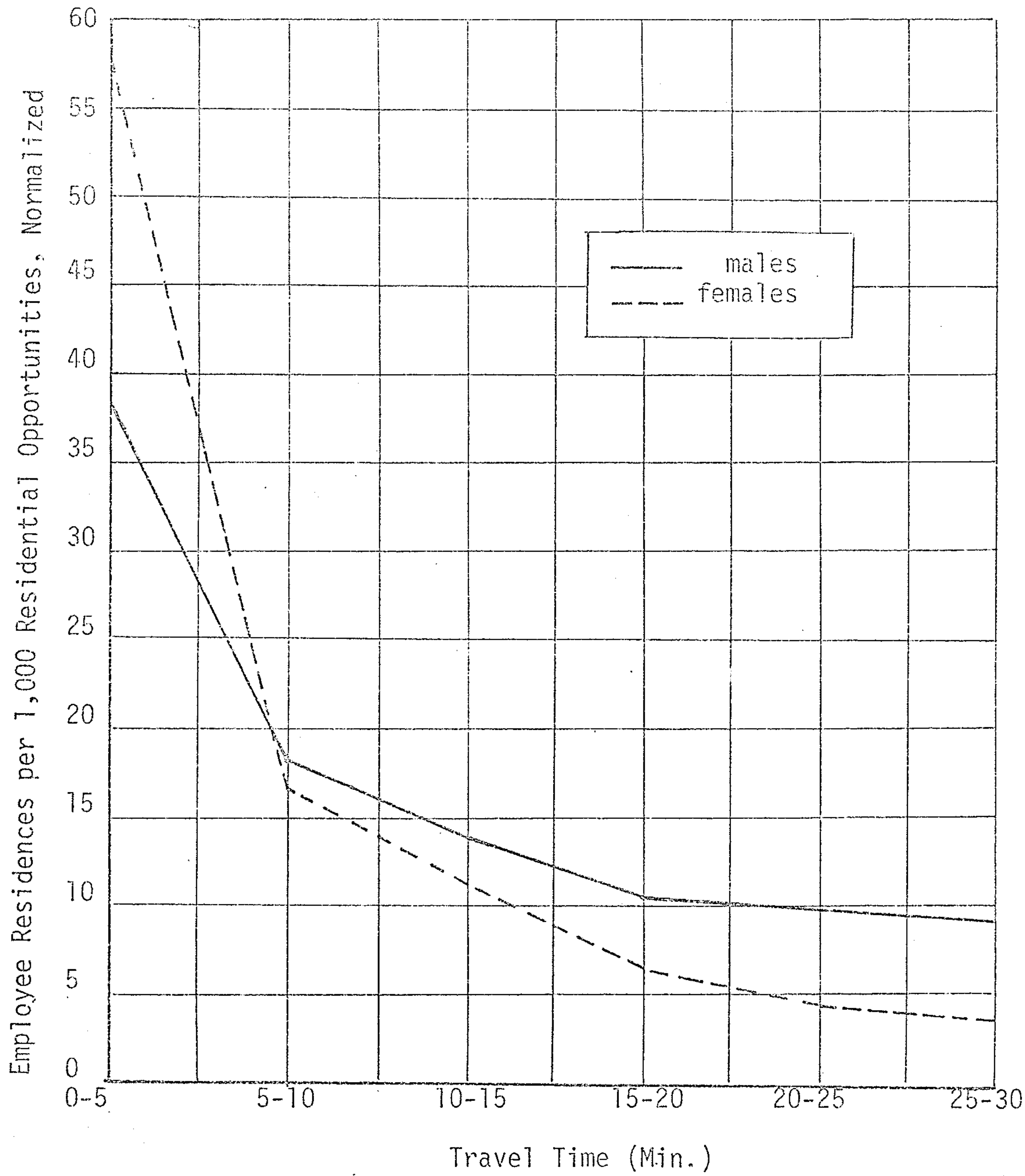

Figure 9: The Normalized Distribution of Employee Residences per 1,000 Residential Opportunities for Males and Females.

Among employees of the same sex, there also seem to be variations in travel propensity by occupation group, as evidenced in differences between average commuting time and average opportunity spacing.

Employees in higher-paying management, professional and technical occupations (Group A) tend to travel further, given the average spacing of their residential opportunities than either those in clerical and sales occupations (Group B) or those in blue-collar occupations (Group C). Although all occupation groups tend to reduce their work-residence separation below that which could result, if they merely selected their homes from suitable opportunities at random, the attempt to limit the length of the journey to work is strongest among blue-collar workers who have the widest opportunity distribution.

White-collar males do not actually travel any further than their blue-collar counterparts; however, they have a much greater chance of finding a suitable residence in proximity to Area No. 1, which is located in the suburbs on the south side of the city. This is a reversal of the situation generally faced by employees of Central Business Districts where blue-collar residences are traditionally closer.

The normalized distribution of employee residences, per one thousand residential opportunities for males in the three occupation groups, is presented in Figure 10.[1] It suggests that the travel flexibility and

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1 These travel propensity distributions were also tested to determine if they are statistically significantly different from one another. Using the standard error of the difference between the means, the distribution for males in Group A was found to be significantly different from that of Group B at a 95% level of confidence and different from that of Group C at a 99% level. Group B's distribution was found to be significantly different from Group C's at an 80 % level of confidence. Approximately the same results were obtained using the Kolmogorov-Smirnov test.

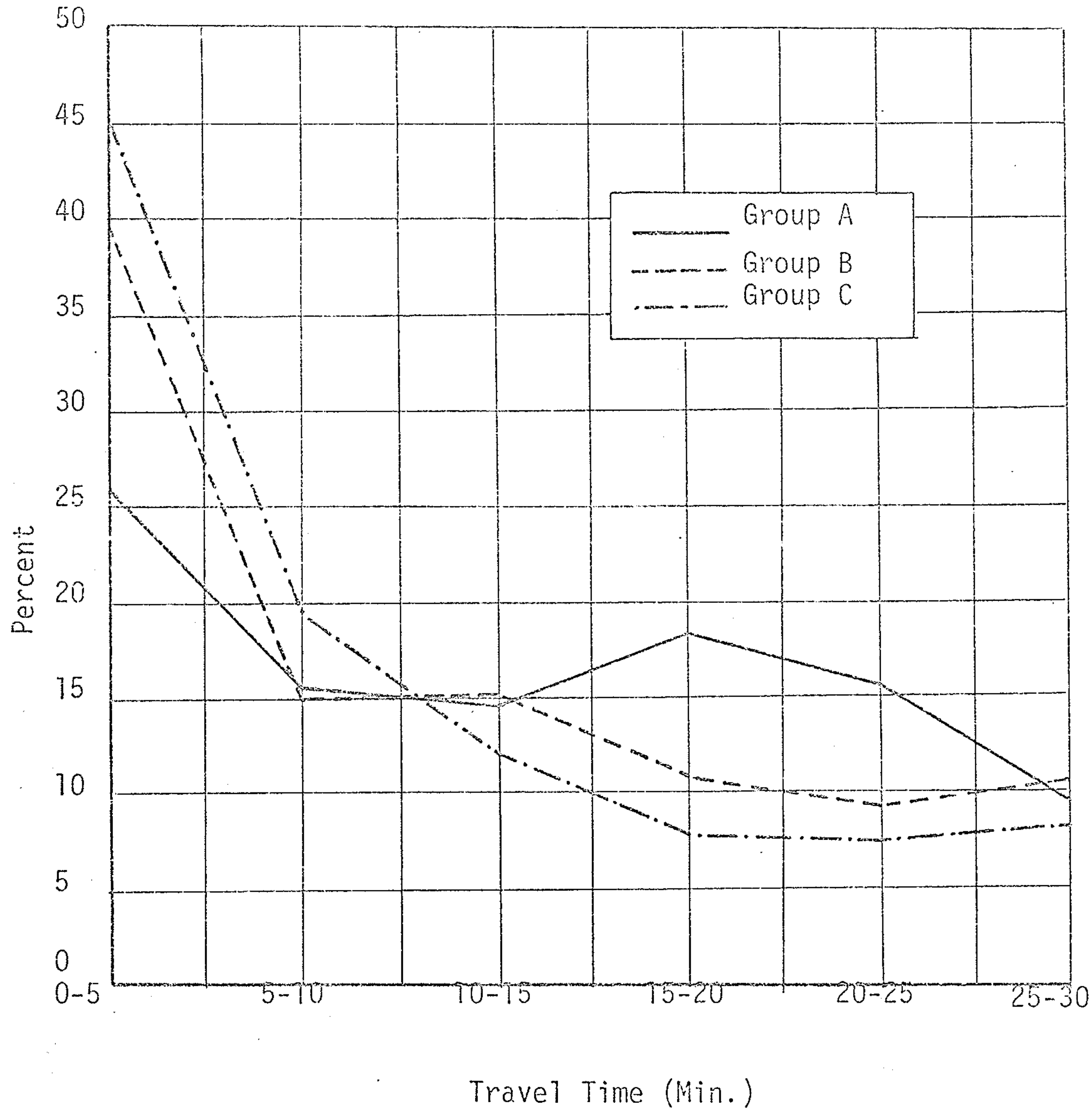

Figure 10: The Normalized Distribution of Employee Residences per 1,000 Residential Opportunities for Males in Three Occupation Groups.

housing freedom of choice, afforded by higher income occupations, is an important factor in accounting for worktrip travel time differences between occupation groups. This is somewhat contrary to Voorhees' position, cited in Chapter II, that occupational variations are little more than reflections of differences in the traditional distribution of residences housing each group.

Table 8 indicates that the Red and Assiniboine Rivers constitute psychological travel barriers to employees of Area No. 1. Within the ten to fifteen and fifteen to twenty minute travel time intervals, a greater proportion of employees reside on the same side of the rivers as their place of work than one would expect, given the distribution of residential opportunities. This is not true of the five to ten minute interval, where a higher ratio of employees to opportunities was found in one census tract, number 103, on the opposite side of the Red River. This small discrepancy is not considered to be significant and is probably due to the area's convenient location immediately across a bridge and its high level of residential amenity.

Table 9 shows that the inner-city area is also a psychological barrier to Area No. 1 commuters. The number of employee residences per one thousand opportunities is higher on the suburban side of Area No. 1 than on the inner-city side within all applicable travel time intervals except the five to ten minute zone. This interval is located entirely on the destination side of the Central Business District and commuters residing there can take advantage of travelling against the major peak hour traffic flow for their entire journey to work.

A comparison of the observed travel time distribution and that predicted by various spatial interaction models for blue-collar males is presented in Figure 11. As outlined there and in Table 10, the Gravity Model with travel time raised to a negative power serving as an impedance factor gave the best fit with observed frequencies of the four models tested. The exponential form of the Gravity Model also provides an acceptable fit when the employee sample is disaggregated according to sex and occupation group.

Although the exponential form of the impedance function did not perform quite as well in the goodness of fit tests, this does not imply that a function of the form $t_{i,j}^{-x}$ is to be preferred generally. The tests were based on one sample only and the size of the zones involved were very large. Previously cited research indicates that the exponential form usually performs better for extremely short or long trips, which would be more prevalent in a region divided into a greater number of zones.

Statistically significant differences between observed and theoretical frequency distributions were found for both Opportunity Models using the Chi-square test and just for Tomazinis' model using the Kolmogorov-Smirnov test. Schneider's version generally produced a closer fit than Tomazinis', which is undoubtedly due to the adjustment permitted by the L parameter in the former. Given the variation in travel propensities, indicated previously, it is not surprising that the Opportunity Models, which rely solely upon the distribution of opportunities, did not predict as well as the Gravity Models, which also consider travel impedance.

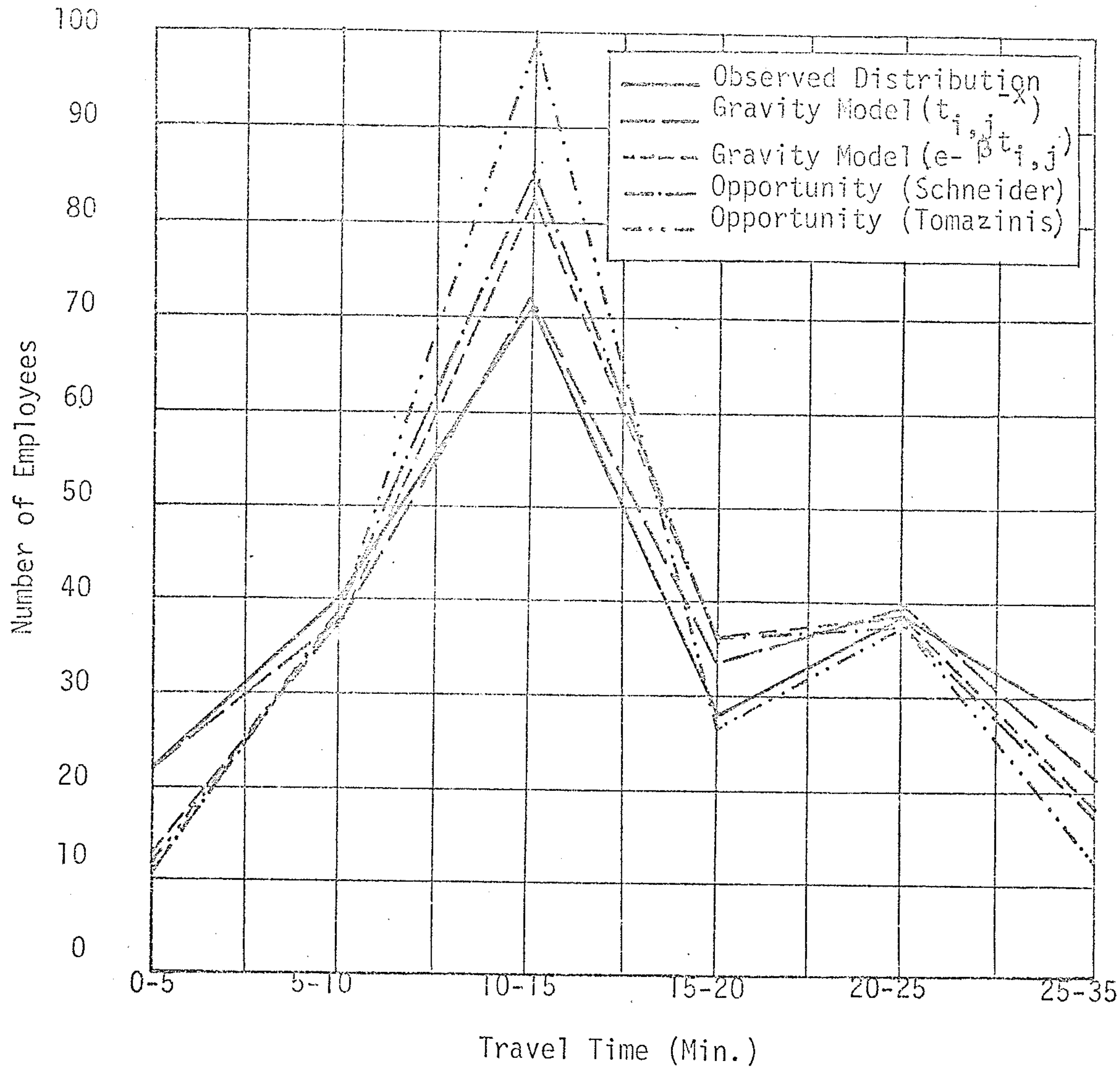

Figure 11: A Comparison of Observed and Predicted Work Trip Travel Time Distributions for Male, Blue-Collar Employees of Fort Garry Industrial Area No. 1.

The variation in model parameters found in Table 10 is further direct evidence of variation in travel propensity. As the x, β and L parameters decrease, longer trips become more likely.

Previously indicated research concluded that model parameters decrease as the mean opportunity spacing increases; which on a city-wide basis occurs with increasing distance from the Central Business District. For the suburban industrial area under discussion, the parameters decrease as the opportunity spacing decreases. This would seem to indicate that there is no uniform relationship between travel propensity and opportunity spacing per se. Instead, Alan Wilson's theory that travel propensity increases with the trip-maker's income appears to be borne out.

Sources of Error

It should be stressed that any conclusions, however appealing, reached on the basis of a single, limited case study should be viewed with some caution. It is appropriate at this point to identify some of the possible sources of error introduced by the procedure undertaken above.

There is always some question as to whether or not the sample taken is representative of the population under study. In this case, the population involved might be limited to the employees of Fort Garry Industrial firms which established in Area No. 1 between 1961 and 1971. Since a hundred percent sample of this population was attempted, the only sampling bias possible might be due to nonresponse. However, only one firm out of fifteen did not respond and the number of employees excluded is estimated to be less than one hundred. Since there is no reason to believe these employees are much different from those sampled in terms of their work travel propensties, and because nonrespondents are a very small proportion, it is reasonable to assume that the sample is representative of the population, as defined.

On the other hand, one might consider the population involved to be the entire working force of Winnipeg. In this case, there is the possibility of considerable bias due to the manner in which the sample was taken. The sample was not drawn randomly from all the workers in the city but limited geographically and temporally according to the employer's location. Such a sample might be considered a judgement sample, since the judgement of the researcher is involved in selecting the elements to be included. Judgement samples are suitable for pilot studies where further research is indicated and where cost and convenience are paramount, as in the case at hand. However, because the majority of the population was excluded from the possibility of selection and consideration, the sample, despite its large size, is suspect; and the use of statistical methods based on the laws of probability, such as the computation of sampling error, is questionable.[1]

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1 If our sample, or strata within it, had been drawn randomly from the working population of Winnipeg, it would be possible to determine a sampling error or the precision of derived population estimates for a given level of confidence based upon the sample size and, to a lesser degree, the proportion of the population involved. For example, a random sample of 749 with the distribution observed herein would be sufficient to estimate mean commuting times for all city workers within $\pm$ 0.7 minutes of the sample mean at a 99% level of confidence. However, since randomness was not assured, such calculations are not particularly relevant.

There are several possibilities regarding the nature of possible bias. For example, major differences in average income level, length of employment, average opportunity separation and level of opportunity awareness characteristic of workplaces other than Fort Garry Industrial Area No. 1 might significantly alter the work-residence separation of the population relative to the sample. Stratification by sex and occupation group and accounting for a specific opportunity distribution in the determination of travel propensities would eliminate a great deal of variation due to these factors. However, whether or not the sample is still representative of Winnipeg workers, despite the potential for bias, could only be determined by testing whether the distributions for the sample population and the total population are statistically significantly different. As the appropriate total population parameters are not available, such tests can not be conducted and the observations and conclusions presented here must, strictly, be limited to employees of Fort Garry Industrial Area No. 1.

There are also several possibilities for measurement bias or error in the survey and analysis procedures employed. For example, the travel time intervals described in Map 3 may not be completely accurate due to:

1) differences in zone to zone travel times between 1971, when that data was computed, and 1974, when the employee sample was obtained;

2) differences between zone to zone travel times simulated as part of Winnipeg's transportation planning procedure, and travel times actually experienced by the individual commuters;

3) the difference in the location of the centroid of traffic zone 442 and the centroid of Industrial Area No. 1, which occupies the western part of zone 442;

4) variations in intrazonal and terminal travel times not reflected in the centroid to centroid travel time data employed; and,

5) inaccuracies due to the interpolation of travel time isolines by hand using a limited number of data points.

In addition, there may be considerable information masked in the distributions obtained because of the rather gross level of zonal aggregation used. There was, however, a trade-off necessary between refinement of the distribution and the need to maintain sufficient observations in each time interval as well as the desire to approximate the travel time perception of the individual commuter. Given the rather large intervals which result, the use of the midpoint as an average travel time for the employees or opportunities in an interval may not be a valid assumption, if their distribution within the interval is skewed.

A further source of error may be inherent in the procedure used to allocate census tracts to time intervals. Residential development in certain tracts was actually split between time intervals, although it was all allocated to the interval where the majority appeared to be located. Some intervals may have incorrectly gained or lost both employees and residential opportunities in this process.

Minor errors might also be present in the designation of sex, occupation and census tract of residence for each employee. These may have occurred because of:

1) clerical errors on the part of the firms providing the sex, occupation and addresses of their employees;

2) errors in assigning poorly-defined occupations to a particular census group; and

3) errors in assigning addresses to the correct census tracts where only the nearest hundred block address was available.

Finally, the number of opportunities assumed for each travel time interval may be in error for the following reasons:

1) It was assumed that the working population in a particular interval is a good estimation of the actual residential opportunities available there. This is only valid if there is a relatively-uniform rate of worker occupancy and dwelling unit vacancy across the city. Reasonably however, these must be expected to vary somewhat over time and from one interval to another.

2) Workers living in residential areas which developed between 1971 and 1974 were not reflected in the 1971 census data; however, these areas identified on Map 4, were a source of potential housing for employees of Area No. 1 in 1974.

3) Minor errors in the number of workers in each census tract may be present due to the process of random rounding to the nearest five individuals, used for the 1971 Census.

Although caution is warranted, it should not be assumed that the results obtained are invalid. Many of the measurement errors specified are either very minor, could be uniformly distributed across the intervals, or could cancel one another. The very fact that the results obtained generally coincide with those of other researchers in the field is significant confirmation of their validity.

CHAPTER 4

SUMMARY OF CONCLUSIONS AND IMPLICATIONS FOR URBAN PLANNING

Based on the analyses undertaken in previous chapters, a number of important conclusions about the separation of work and residence and their implications for urban planning can be put forward.

First, employees of a specific workplace diminish as a proportion of resident population with increasing travel time-distance from that place of work according to a negative exponential or negative power function. Given that, it is possible to predict the residential, employment, or worktrip interchange distribution for groups of individuals.

Of the analytical mathematical models of worktrip interaction currently available, the Entropy-maximizing Gravity Model is probably the most promising in terms of its performance, its statistically valid theoretical derivation, its suitability for systematic disaggregation, and its potential for integrated and dynamic modelling of transportation planning and residential location processes.

Given widely varying travel propensities between groups of workers, it is still necessary to conduct origin-destination surveys to calibrate model parameters. Systematic disaggregation of worktrip travel according to the age, sex, family size, income, occupation and perhaps zone of origin of the tripmaker may reduce the levels of adjustment required somewhat. Of these variables, occupation, and possibly sex and income, are probably the most useful for disaggregation purposes, since they permit a stratification of opportunities at both ends of the trip, as well as account for variation in travel propensity. Too much disaggregation can result in a loss of statistical relevance, and imponderable changes in opportunity attractiveness, vacancy rates, consumer preference, awareness, and average travel expenditures will ensure the necessity for some calibration. Furthermore, socio-economic adjustment factors may be required to account for inordinate levels of interaction between certain zones caused by concurrent development, historical community identification, social and ethnic ties, psychological travel barriers, and the inertia of adjustment to major changes in employment or residential opportunity distributions.

Additional work is required to determine the best form of travel impedance function for different situations; although, intuitively it seems that a negative exponential function of travel time, or possibly intervening opportunities, is most suitable to intraurban travel, while a negative power function of generalized travel costs is preferable for longer interurban trips.

In large Canadian urban areas, including Winnipeg, most people are willing to spend in the order of fifteen to twenty minutes in getting to work, almost irrespective of the travel mode they employ. This means that expenditures on transportation improvements designed to decrease or maintain travel times will never be very productive. They simply en-

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1 Hanlon, "National Survey", p. 8.

courage more people to travel further in order to exercise their tastes and preferences for homes and jobs. On the other hand, the distribution of suitable opportunities about an origin does have on impact on travel time. The more compact the opportunity distribution, the lower the average trip length.[1] This suggests that providing complimentary residential and employment opportunities in close proximity to one another increases the chances of reducing or limiting commuting. A recent policy report prepared by the Greater Vancouver Regional District states:

> ...if trends continue, more people will be living further away from work, and the other places they want to go. The cost of providing additional roads and public transportation to help more people travel further and as fast as they now do is simply more than the region can afford. Thus, only by bringing needed activities closer to home can their accessibility to people be maintained.[2]

At a metropolitan level, there should be less emphasis on peripheral growth and more on infill growth and increasing densities. Residential and employment concentrations should be limited in size, and dispersed between one another to create a fine grain urban structure.

At a more detailed level it must be recognized that suitable residential and employment opportunities are narrowly circumscribed for certain groups and some have a greater propensity or ability to travel than

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1 Voorhees et al, "Factors in Work Trip Length", p. 26.

2 "Regional Town Centres: A Policy Report", the Greater Vancouver Regional District (November 1975), p. 21.

others. This implies that residential areas closest to an employment area should provide a quantity and quality of housing suited to the particular needs of the workers employed there. Moreover, those with the least propensity or ability to travel should be given priority in terms of proximity to their place of work.[1]

To generalize somewhat, the commuting pattern observable in most North American cities today consists of blue collar inner city residents travelling to suburban industrial districts, while white collar suburbanites commute to downtown office jobs. Simply stated, there are four possible alternatives to reverse this situation:

1. increase blue collar housing in the suburbs;
2. increase white collar employment in the suburbs;
3. increase blue collar employment downtown; or,
4. increase white collar housing downtown.

Clearly the situation is more amenable to change in new growth areas and the first two options are by far the most feasible. There are some encouraging signs of changes in this direction through the creation of commercial subcenters and suburban industrial parks, as well as provision of more affordable rental and multi-family housing in the suburbs. The Greater Vancouver Regional District decided, "that it would

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1 The creation of socio-economic "ghettos" must also be avoided The objective is to increase access to all kinds of opportunities not to limit it.

be impossible to achieve an overall balance between jobs and population in each part of the Region, but that a policy of creating new jobs in suburban municipalities at the same pace as their residential growth was achievable."[1]

Besides limited opportunities for substantial redevelopment, such as rail relocation schemes, the major problem in balancing homes and jobs in the central parts of cities is the space requirements of manufacturing and most other industry, as well as those of the large portion of the population in the child-rearing stages of their life cycle. Land values are so high in central areas that these uses are increasingly eliminated. For all practical purposes, downtown opportunities are limited to commercial, office, and service employment, as well as high density housing catering primarily to singles and couples.

On the other hand, in newly developing areas there are a number of planning measures that may be effective in promoting reduction in commuting.[2] These are:

1) The creation of compact, self-contained communities with a balanced range of employment and housing opportunities for groups of varying income, occupation, family size, mobility and tenure preference;

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1 "Regional Town Centres", p.20.

2 Financial incentives and other implementation programs aimed at balancing residential and employment opportunities are beyond the scope of this thesis.

2) The provision of a minimum standard of residential amenity in each community;

3) The provision of a subcentre-oriented transit and roadway system so that local opportunities are the point of transfer to service to other employment, commerical and recreation centres;

4) The use of psychological travel barriers, where appropriate, as boundaries for self-contained communities;

5) The promotion of a high level of community identification and opportunity awareness through active local news media; and,

6) The maintenance of a reasonable housing vacancy rate throughout the city to allow individuals to find accommodation in the community where their job is located.

Given limited experience with purposeful attempts at reducing worktrips travel such as those described above, it is difficult to say what degree of improvement might be achieved. While research to date indicates providing more convenient, suitable opportunities to be the most promising approach to the problem, with freedom of choice and uncertain psychological motives, there will probably always be a good deal of commuting beyond optimal minimums.

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